AN INVESTIGATION OF MERCURY AS A HIGH-SPEED ELECTRICAL CONTACT

R. G. SHULTS

RESULTS &
APPENDIX

This work is accepted as fulfilling the thesis requirements for the degree of Master of Science in Electrical Engineering from the United States Naval Postgraduate School.

AN INVESTIGATION OF
MERCURY
AS A
HIGH-SPEED ELECTRICAL CONTACT

R. G. SHULTS

AN INVESTIGATION OF

MERCURY

AS A

HIGH-SPEED ELECTRICAL CONTACT

By

R. G. SHULTS
Commander, United States Navy

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

United States Naval Postgraduate School
Monterey, California
1952

AN INVESTIGATION OF
MERCURY
AS A
HIGH-SPEED ELECTRICAL CONTACT

Preface

The use of carbon as a medium for transferring electrical currents between two pieces of copper moving at different, and often high, relative speeds is a long-established and adequately successful practice; that is, it is a practice successful at sea level and at the lower altitudes. The growth of the electrical load in aircraft, coupled with its ability to reach ever-increasing altitudes has led to failure of the standard carbon brushes. The reasons for the failure of carbon brushes at high altitudes are not well known, but are believed due to the deterioration of the lubricating qualities of standard air at the higher altitudes. The nature of the carbon brush failure is an accelerated wearing away of the brush in a matter, sometimes, of minutes, whereas at sea level it might have lasted for years at the same speed and current density.

In recent months much has been done to increase the life of the carbon brush at high altitudes. One manufacturer reports a specially impregnated carbon brush with a high altitude life of some 750 hours. On the other hand, certain of the steps taken to make the carbon brush more durable at high altitudes have rendered it short-lived at the lower

AN INVESTIGATION OF
MERCURY
AS A
HIGH-SPEED ELECTRICAL CONTACT

Preface

The use of carbon as a medium for transferring electrical currents between two pieces of copper moving at different, and often high, relative speeds is a long-established and adequately successful practice; that is, it is a practice successful at sea level and at the lower altitudes. The growth of the electrical load in aircraft, coupled with its ability to reach ever-increasing altitudes has led to failure of the standard carbon brushes. The reasons for the failure of carbon brushes at high altitudes are not well known, but are believed due to the deterioration of the lubricating qualities of standard air at the higher altitudes. The nature of the carbon brush failure is an accelerated wearing away of the brush in a matter, sometimes, of minutes, whereas at sea level it might have lasted for years at the same speed and current density.

In recent months much has been done to increase the life of the carbon brush at high altitudes. One manufacturer reports a specially impregnated carbon brush with a high altitude life of some 750 hours. On the other hand, certain of the steps taken to make the carbon brush more durable at high altitudes have rendered it short-lived at the lower altitudes. A comprehensive review of the high-altitude carbon brush-dusting problem may be found in Ref. 1.

As a partial answer to the problem, this investigation was initiated. Reasoning was along these lines: If a solid type of brush is troublesome, could a liquid type, of necessity enclosed, be designed to be less troublesome? The liquid, of course, should be a good conductor, should be easy to handle and contain, should be readily available, but need not necessarily be inexpensive if it could eliminate electrical power failure in modern military aircraft now caused by carbon brush dusting.

A good many fluid conductors of electricity immediately suggested themselves, but one of the best and most common, the fluid metal mercury, was almost an obvious first choice, particularly since Faraday had suggested its use in connection with the homopolar machine (see Ref. 2).

As a first step then, in August 1951 an idea for a test vehicle was sketched and presented to Professor C. V. O. Terwilliger, Head of the Electrical Engineering Department of the U. S. Naval Postgraduate School, then at Annapolis, Maryland. Dr. Terwilliger considered the idea worthy of thesis investigation as part of the requirements leading to the award of a Master's Degree in Electrical Engineering. Consequently, the device was designed and built at Annapolis, being completed by mid-November 1951.

Due to the moving of the Postgraduate School to Monterey, California in late November 1951, actual testing was delayed altitudes. A comprehensive review of the high-altitude carbon brush-dusting problem may be found in Ref. 1.

As a partial answer to the problem, this investigation was initiated. Reasoning was along these lines: If a solid type of brush is troublesome, could a liquid type, of necessity enclosed, be designed to be less troublesome? The liquid, of course, should be a good conductor, should be easy to handle and contain, should be readily available, but need not necessarily be inexpensive if it could eliminate electrical power failure in modern military aircraft now caused by carbon brush dusting.

A good many fluid conductors of electricity immediately suggested themselves, but one of the best and most common, the fluid metal mercury, was almost an obvious first choice, particularly since Faraday had suggested its use in connection with the homopolar machine (see Ref. 2).

As a first step then, in August 1951 an idea for a test vehicle was sketched and presented to Professor C. V. O. Terwilliger, Head of the Electrical Engineering Department of the U. S. Naval Postgraduate School, then at Annapolis, Maryland. Dr. Terwilliger considered the idea worthy of thesis investigation as part of the requirements leading to the award of a Master's Degree in Electrical Engineering. Consequently, the device was designed and built at Annapolis, being completed by mid-November 1951.

Due to the moving of the Postgraduate School to Monterey, California in late November 1951, actual testing was delayed until April 1952. The nature of the testing and the results obtained are herein set forth.

It is at once apparent that a fluid brush would not be compatible with a commutator; hence, it was considered only for its use with a slip-ring. In this connection, then, one must keep in mind that even though the fluid brush might be successful in solving the high-altitude brush problem, it would eliminate the commutator and make necessary the employment of the homopolar machine either for main direct current generation or for dc excitation for the alternator. Thus, a secondary problem arose requiring investigation: could the extra weight and size, if any, of the homopolar machine be tolerated?

Because time ran out and because this investigation and a report of it had of necessity to be completed by June 1952, the mercury brush was little more than made ready for a sea-level test and the secondary problem was not approached at all.

Thus there remains considerable investigation at sea level, and the total investigation in an altitude chamber, plus any flight testing which might ultimately be indicated.

It follows that the success or failure of mercury need not preclude further investigation of the many other fluid conductors, nor of the homopolar generator as an exciter, for other reasons.

until April 1952. The nature of the testing and the results obtained are herein set forth.

It is at once apparent that a fluid brush would not be compatible with a commutator; hence, it was considered only for its use with a slip-ring. In this connection, then, one must keep in mind that even though the fluid brush might be successful in solving the high-altitude brush problem, it would eliminate the commutator and make necessary the employment of the homopolar machine either for main direct current generation or for dc excitation for the alternator. Thus, a secondary problem arose requiring investigation: could the extra weight and size, if any, of the homopolar machine be tolerated?

Because time ran out and because this investigation and a report of it had of necessity to be completed by June 1952, the mercury brush was little more than made ready for a sea-level test and the secondary problem was not approached at all.

Thus there remains considerable investigation at sea level, and the total investigation in an altitude chamber, plus any flight testing which might ultimately be indicated.

It follows that the success or failure of mercury need not preclude further investigation of the many other fluid conductors, nor of the homopolar generator as an exciter, for other reasons.

R. G. Shults

CDR R. G. Shults, USN
Section AE3
U. S. Naval Postgraduate School
Monterey, California
June, 1952

CONTENTS

CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF TABLES

AN INVESTIGATION OF

MERCURY

AS A

HIGH-SPEED ELECTRICAL CONTACT

Summary

In seeking a possible substitute for the carbon brush for aircraft use, the idea of using mercury as a fluid contact was investigated.

It was found that a mercury-steel combination appeared to be satisfactory electrically at sea level.

It was further found that the voltage drop across the moving mercury-steel contact appeared to be independent of the current flow through the contact and of the relative speed of the contact surfaces.

AN INVESTIGATION OF MERCURY AS A HIGH-SPEED ELECTRICAL CONTACT

Equipment

A fluid conductor brush must take the general form of two solid conductors separated by the fluid in order to permit relative motion. A typical usage would find one of the solid conductors fixed; the other moveable. While an experimental design along these lines would have been preferred as simulating actual conditions more closely, but because it was desired that its performance at high peripheral speeds be known, the mercury brush was designed so that both solid conductors could move in opposite directions. This led to unsatisfactory operating conditions at high speeds as will be pointed out later.

Consequently, the test mercury brush as built took the form of a steel disc rotating in a pool of mercury contained in a steel cylinder rotating in the opposite direction. The use of steel in the presence of mercury was again an almost obvious first choice, since mercury dissolves all common metals as amalgams except iron, platinum and nickel.

Concerning the size to make the test brush there was little to go on, and it was decided to keep it fairly small since if it should burst for any reason, the danger to those

about it would be greatly minimized. As a further consideration, ready-made drive shafting and matching bearings with pedestals were immediately available and were of such size that a large mercury brush was inadvisable. In order to further reduce danger due to bursting, the walls of the cylinder were made much thicker than necessary. This also led to an operational problem to be pointed out later.

It was necessary to provide some sort of seal about the entering disc shaft to prevent any tendency for the mercury to leak. This took the form of a close-fitting machined-pressed paper insert, screwed to the cylinder face. This, too, proved a troublesome spot until late in the test period.

To provide for interim inspection of the interior of the brush, the shell of the cylinder was made so that it could be unscrewed and the disc withdrawn. This feature also proved a problem at high speeds and although never solved in this series of tests, its solution would be no problem in future tests, as will be pointed out.

Since mercury boils at sea level at about 356.9° C. and since it was not known what the heat generation might be in the brush, it was thought necessary that some means of recording temperature be provided. This was effected by drilling out the center of the two drive shafts to permit insertion of thermometers. This feature proved very helpful and gave no trouble directly, although it contributed to a hot-spot

problem, as will be pointed out. The sensitive elements of the thermometers were thus placed almost at the center of the brush.

To provide a means of driving the two elements of the brush, two 4-step cone pulleys were mounted on the shaft to be belt-driven by two D.C. motors. These motors were Marathon Electric 1/8 HP, shunt-wound, 115 V, 1.3a, 1725 rpm, type DS motors. To provide speed control in addition to that inherent in the pulleys, rheostats, 100 ohms and 800 ohms, respectively, were placed in both armature and field circuits of the driving motors. This feature permitted excellent speed control throughout the test period.

To get current to the mercury brush since it was not a part of any sort of generating device and because both parts of it rotated, it was necessary to resort to carbon brushes and brass slip rings--brass because copper was not available and because the phenomena occurring at the carbon brushes would have no effect on the mercury brush anyway. To this extent, a sort of loose comparison of the two brushes unfolded as they operated side-by-side under identical conditions during the tests. Carbon brushes and holders were salvaged from an aged surveyed repulsion-induction motor and a mounting bracket of bakelite was fashioned to permit two carbon brush sets to operate in parallel on each of the two brass slip rings. This arrangement proved entirely satisfactory.

The apparatus in its entirely was mounted on a large steel plate to provide dimensional stability and mechanical damping.

This, too, was most satisfactory. It was at once obvious, however, that if the drive shafts were to be current conductors, insulation from this steel plate was necessary. This was easily accomplished by mounting the bearing pedestals on pressed paper, by mounting the pulleys on pressed paper sleeves, by using non-conducting v-belts, by setting the carbon brush holders in bakelite as already mentioned and by using insulating tape to keep the thermometers from rotating. At no time during the tests did grounds develop.

To provide a uniform length of path for current flow through the mercury, the disc edge was made circular in cross-section and the interior of the cylinder was so machined that the distance from the disc to the cylinder was 1/8" in all directions. There was no particular reason for this gap length; further tests would surely establish an optimum.

The test mercury brush as described thus far was designed by the investigator and built by Mr. Joseph Octavek of the Machine Shop Section of the Postgraduate School. It must be pointed out here that the failures which occurred were faults of design, whereas the ability of the device to withstand testing as it did was a credit to the great care which Mr. Octavek exercised in putting the device together. The drawing from which it was built and assembled appears as Fig. 1, placed at the back of the report because of its large size. A close-up photograph of the brush assembly is shown by Fig. 2.

Although the Postgraduate School resumed classes in February 1952, tests were delayed because of lack of power at the laboratories. When 3-phase AC power did become available, DC power also became available from any one of a number of motor-generator sets in the laboratory. This was thus the source of power. Voltage for the driving motors was taken from the house DC bus. An independent M-G set was operated to supply DC power to a standard load resistor bank which was fed through the test brush assembly. In this way, variation of load on the test brush could have no effect on the driving motor voltage and thus made for better speed control as well as load control.

The load resistor bank consisted of three separate banks, each of 24 amperes capacity at 125 volts, connected in parallel to provide up to 72 amperes. The generator feeding the load bank was rated at 110 volts, 59 amperes. To keep the carbon brush current density below 50 amperes per square inch, no more than 48 amperes were ever fed through the brushes.

To provide forced ventilation since the presence of mercury vapor was a distinct possibility, two ordinary 18" fans were provided. It later developed that by placing one of the fans quite close to the brushes, enough cooling was provided to permit extension of the tests.

In addition to the thermometers, which were Weston Model 226 calibrated from 0 degrees C. to 200 degrees C., other measuring devices were provided as follows.

To measure rotary speeds of each pulley, two Strobotacs were mounted to flash continuously and directly on the pulleys as shown by Fig. 3, Serial No. 16611 was directed on the disc pulley; Serial No. 16756 on the cylinder pulley. The Strobotacs were of two speed ranges: 600 to 3000 rpm and 2400 to 15000 rpm.

To measure brush current, a Weston Model 45 DC ammeter Serial No. 59320, scale 0 to 50 amperes was placed in series with the brushes. Its calibration curve is given by Fig. 4.

Mercury brush voltage was taken with a General Electric 100,000 ohms per volt DC voltmeter, Serial No. 1112214, scale 0 to 3 volts, whose calibration curve appears as Fig. 5. Picking off the voltage drop across the mercury brush was something of a problem never satisfactorily solved, as will be discussed. Pickoff was provided by two thin brass leaves riding on the inside faces of the two brass slip rings, as shown at points A in Fig. 2.

For no particular reason other than to provide information for the previously mentioned loose comparison of the performance of the carbon brush vs. that of the mercury brush, the drop across the entire brush assembly; i.e., the carbon and mercury in series, was taken by a Westinghouse 5000 per volt DC voltmeter, Serial No. 2357120, scale 0 to 10 volts. Calibration curve for this meter is given by Fig. 6.

The load voltage applied to the brushes was taken by a Westinghouse 5000 ohms per volt DC voltmeter, Serial 2357110, scale 0 to 500 volts. This meter was not calibrated.

Two side views of the complete test assembly are given by Figures 7 and 8. A steel shield, not shown, was provided

to cover the rotating parts during the test--it proved necessary. It did not restrict air-flow from the fans.

PROCEDURE

The period 22 April 1952 through 11 May 1952, ten working days, was consumed in readying the device for test. Twenty-three formal tests in which data were taken were conducted from 12 May 1952 through 26 May 1952, actual tests being made on only ten working days of this period. A log of the entire experiment was kept and is included herein as Appendix A.

Test procedure was simple enough. Only three quantities, in general, were permitted to vary. These were:

(1) Brush Current

(2) Brush Relative Speed

(3) Mercury Volume (and hence current density in the mercury)

For each test, readings were recorded of brush load supply voltage and current, voltage drop across the entire (carbon in series with mercury) brush assembly, voltage drop across the mercury brush alone, rpm of each shaft, and temperature at the centers of the disc and of the cylinder. Beginning with Test No. 11, elapsed time readings were taken along with all other readings.

For tests No. 11 through 23, one of the 18" fans was moved to within 12" of the mercury brush as shown clearly by Fig. 3, providing, it was estimated, some one or two inches of water blast air cooling.

For Tests No. 1 through 19, the mercury level was maintained at what is designated herein as Level A. Level A was that created by the placing of about 15.5 cc of Hg in the cylinder, whose capacity to contain 100% mercury was computed as 21.5 cc. This, depending on how one considered the displacement of the mercury during rotation, gave rise to a contact area on the disc (the minimum) of 6.11 or of 7.80 square inches.

The mercury level was reduced to Level B for Tests No. 20 and 23. This level provided an estimated minimum mercury contact of 3.63 square inches.

Tests No. 21 and 22 were conducted at Level C, which furnished a minimum mercury contact area of some 1.45 square inches.

As mentioned previously, maximum current ever passed through the brush was 48 amperes, which amount to 50 amperes per square inch through the carbon brushes. Actually, the carbon brushes functioned very well, but to prevent any loss of test time due to failure of the carbon brushes, old, of peculiar size and whose composition was unknown, it was decided to set this limit. On the other hand, 48 amperes represented a reasonable load on the rated 59-amperes generator which had just made a transcontinental trip; also the breaker was set for 50 amperes.

A graphical presentation of current density variation is given by Fig. 9, based upon the above calculations of

minimum mercury contact area.

For tests No. 1 through 18, the cylinder was the positive (+) terminal; for tests No. 19 through 23, the disc was the positive terminal.

For tests No. 1 through 18, the carbon brush pressure was the maximum (actual value not determined); for tests No. 19 through 23, the carbon brush pressure was the minimum (actual value not determined).

RESULTS &
DISCUSSION

TABLES

ILLUSTRATIONS

APPENDIX

RESULTS &
DISCUSSION

RESULTS

Of the 23 tests, the first four were excluded from consideration on the basis that they were conducted at speed levels below that of interest. The first four tests were intentionally so conducted in order to permit observation of the test device in operation as designed before the higher speeds were attempted.

The data taken as listed under the Procedure Section was put into tabular form; certain derived factors added; certain averages taken and included herein as Tables I through XV. Current densities both for the carbon and mercury were computed, as was the carbon brush drop. A curve of current densities, already mentioned, appears as Fig. 9. Also computed was the relative speed of the cylinder surface in contact with the mercury with respect to the disc surface in contact with the mercury and moving in the opposite direction. This amounted simply to the sum of the separate peripheral velocities of the two respective surfaces. Figures 10 and 11 show in convenient graphic form the relation between rpm and peripheral velocity as function of diameter.

It is important that the manner of taking the brush drops be noted. Due to the rather poor contact made by the carbon brushes and by the brass spring leaf pickoff's, these two voltages fluctuated through easily detectable ranges as much as 0.2 to 0.4 of a volt. Thus the data recorded in

Tables I through XV reflect the observer's opinion of the value the two meters were attempting to indicate, and may therefore be in error to some extent. This was not true of many readings, however, and in all cases readings were observed long enough (as long as several minutes in some cases) to reasonably establish the mean indication.

In addition to the tabular reduction of the recorded data, certain graphical plots were prepared.

Fig. 12 is a plot of the drop across the mercury brush as a function of contact speed for three different currents for Tests No. 5 through 19. Its source was Tables I through XII.

Fig. 13 shows the same information, plotted on a smaller scale, as Fig. 12, plus the addition of Tests No. 20 through 23, plus the addition of heat rise information on these 19 tests. The additional information was obtained from Tables XVI and XVII. The plotted temperature rise, Table XVII, was the average of the two thermometer indications.

Fig. 14 is a plot of the mercury brush drop as a function of brush current for several different relative speeds. Its source, as well, lies variously in Tables I through XV.

Finally, Fig. 15 is a plot (of Test No. 21 only) of the mercury brush drop vs. time at 10,350 rpm relative (107 f.p.s. relative). This was the greatest speed attained: for various reasons, to be pointed out, greater speeds with the test device in its present form were not possible. Fig. 15

also shows the temperature variation of both disc and cylinder throughout the test. This Test No. 21 was the most thoroughly conducted of all tests, it is believed, and for that reason it was plotted separately. In retrospect, all tests should have been similarly conducted, but as mentioned earlier, the experiment really only reached the point for good testing when it had to be stopped for want of time. Test No. 21 is tabulated in Table XIV.

DISCUSSION

A good understanding of the defects and shortcomings of the test device is a first requisite in evaluating the results obtained. These deficiencies have been raised variously throughout the report.

For the first series of tests; that is, No. 1 through No. 19, the mercury level was the greatest used. In turn, for these tests, current density was least. It was first thought such a volume of mercury would lead to best results, but this was not the case. As the higher rpm were approached three objectionable features became apparent.

The first to be noticed was the high heat generated on the rim of the cylinder due to nothing more than friction. This, in turn, led secondly to expansion of the cylinder and at 3000 rpm absolute, the combination of heat and centrifugal force was enough to permit a fine spray of mercury to be thrown out through the threaded joint by which the two pieces of the cylinder were joined. The canopy shielding the rotating parts proved essential here.

The third objection to the high level of mercury was again mechanical. The oppositely rotating disc seemed to "roll up" the mercury between it and the cylinder. This led to unbalance which at the higher rpm created heavy vibration in the device.

From the heat standpoint, there were two other defects. The walls of the cylinder were 1/4" thick; probably thicker than they need have been by perhaps as much as 3/16". These thick walls, without cooling fins, simply could not radiate heat efficiently enough. Also, since an arbitrary maximum temperature on either thermometer had been established as 100°C, an unnecessary limitation was imposed by the fact the 5/16" shaft had to be provided with a 5/32" core to permit insertion of the thermometers. At the point where the cylinder was screwed on to its shaft, there were two or three threads which did not go fully into the cylinder. This combination of a drilled-out center and exposed exterior threads created a hot spot due to current flow through the very narrow cross-section at this point. It was thus always a question with just what share of the heat was the mercury to be credited. This hot spot is indicated as "B" in Fig. 2.

Another hot-spot problem arose where the pressed-paper seal raced on the disc shaft.

Accordingly, three steps were taken to remedy the above problems. To alleviate the hot-spot at the thin cross-section of the cylinder shaft, a bead of solder was laced about the shaft at "B" of Fig. 2. To reduce heat due to friction within the mercury, the mercury level was reduced (see Fig. 9). To reduce the hot-spot at the seal, it was removed and part of it filed away.

When the device was re-started, it was at once apparent too much of the seal had been removed, but it

coincidentally gave opportunity to note the nature of the turbulence in the mercury. It had been thought centrifugal force was holding the mercury smoothly away from the center and that the seal was not really needed. Actually, there must have been terrific turbulence in the mercury if the degree of leakage through the seal was *any* index. It was also interesting to note the leaking out the seal could be stopped by speeding up the cylinder. This led to a restoration of the seal and a further reduction of the mercury level.

Now, upon re-starting, improvement over initial operating conditions was clearly noted. It was possible now to run the device up to 10,350 rpm relative, and indications were higher peripheral velocities could be obtained.

There was some trouble with voltage pickoff across the mercury brush. At first it had been intended to take this voltage through the bearings. This was a futile proceeding; no voltage indication where voltage was known to be. It was clear after the situation presented itself that the bearing grease was acting as an insulator. The answer was to take the voltage off two brass spring leaf probes riding on the side of the brass slip rings. Even these gave fluctuating voltage readings, though great improvement was attainted simply by smudging the pickoff race with carbon.

It was because of these pickoffs that ohmmeter readings were not taken seriously. Whereas some contact resistance at the probes would have little effect on the

100,000 ohms per volt voltmeter being used, they were thought possibly to show a good deal more resistance than would the mercury. Ohmic readings ran anywhere from 16 ohms to 60 ohms measured across the pickoff's during rotation; at standstill, readings were variously 2 to 5 ohms. The ohmmeter was used mainly to insure a closed circuit through the brush before loading it electrically, as otherwise the full supply voltage would have appeared across the 3-V voltmeter.

In this connection, one inadvertent open-circuit did develop across the mercury brush. Test No. 22 followed Test No. 21 very closely, the first being at 10,350 rpm relative; the second at 6,000 rpm relative. Obviously enough, mercury was thrown from the cylinder at 10,350 rpm almost to deplete it. At the end of Test No. 22 (do see Table XV) during which there was no leakage, when the current was dropped from 25 amperes to only 5 amperes, the brush voltage dropped from 0.35 volt to 0.05 volt and this voltage could be repeated by shutting the current on and off, 0 to 5 amps. Curious over this, speeds were increased toward 10,000 rpm again which immediately opened the circuit at the mercury brush. From this, it appeared that there does exist an optimum minimum mercury volume, or conversely, an optimum maximum current density. It should be obvious here that Fig. 9 is very probably in error concerning Tests No. 21 and 22. Time did not permit looking

into this interesting occurrence any further. It does appear such optimum should be sought and great pains taken to prevent any leaking so that good quantitive information could be obtained.

With this much background, it is now clear to the reader that any observations to be made concerning the experiment should be qualitative only, in spite of the rather formidable mass of data taken.

Fig. 12, a plot of mercury brush voltage drop vs. contact speed, would indicate that the drop increased both with contact speed and current density. However, it may actually be that the drop is independent of either current density or contact speed, and is rather dependent on heat only, since both increase in current density and in contact speed lead to heat generation. It is well known that resistance of metallic conductors increases with temperature. The drop being measured was not strictly across just the mercury. Actually, the drop was being measured across part of each brass slip ring, across about 4" of steel shaft of very narrow cross-section, and across the steel disc and cylinder, all of which became heated along with the mercury.

Fig. 13 seems to indicate a temperature effect rather than a speed or current density effect. Tests No. 20 through 23 were run after the remedial heat-reducing steps discussed earlier were taken. Fig. 13 shows a decrease in voltage drop across the mercury brush for the last four tests as compared to the previous fifteen. For the last four tests, current density was greater than during the previous fifteen and speeds were greater.

Fig. 14 would also appear to support the above opinion. In Fig. 14 the drop across the mercury brush is plotted against current. Here again it may be seen that by reducing the heat generated (Test No. 21), the voltage drop was less at 10,350 rpm than at 6,000 rpm for Test No. 14.

A comparison of Test No. 22 at 6,000 rpm, Table XV, with Test No. 25 at 10,350 rpm, Table XIV, both at about the same current density and both showing similar temperature rises, would appear to indicate the decrease in voltage drop of Test No. 22 was speed motivated.

A comparison of Test No. 22 at 6,000 rpm of high current density with Test No. 14, Table X, at low current density, would seem to show the decrease in voltage drop of Test No. 22 was current density motivated.

None of the effects on the voltage drop across the mercury brush were of great magnitude, however. The voltage drop varied from a minimum (excluding the point at 0.05 volt) of about 0.5 volt at 3,000 rpm relative to a minimum of about 0.7 volt at 10,350 rpm relative.

Although a comparison of the mercury brush against the carbon brush would not be fair in this test, an examination of the data sheets will show the carbon drop to be consistently higher. The carbon brush drop tabulated is that for <u>two</u> carbon brushes in series.

Though not under investigation, the carbon brushes did show some interesting (and well known) characteristics. It was observed that when current was reduced suddenly the

[illegible]

[illegible]

[illegible]

the [illegible]

at [illegible]

A [illegible]

Test No. [illegible]

current [illegible]

would [illegible]

No. 22 [illegible]

A comparison [illegible]

density [illegible] No. 14, [illegible]

would [illegible]

29 was [illegible]

Some of the [illegible]

mercury [illegible]

drop varied from [illegible]

of about [illegible]

about [illegible]

Although [illegible]

carbon [illegible] not [illegible]

of the [illegible]

tests [illegible]. The [illegible]

two cases [illegible]

The [illegible]

show [illegible]

was [illegible]

carbon brush drop would decrease as suddenly to about one-quarter of its original value. Within a few minutes at the reduced current, the carbon voltage drop would build back to its original value. It was also easy to observe the fact that there was less drag of the carbon brushes on their slip rings when current was flowing than when running on open circuit. The carbon brush drop also increased as brush pressure decreased.

Pure mercury was used in this experiment. At no time did any of the leakage mercury appear to have oxidized or to show any other change in appearance. The possibility of a change in the mercury with age in the brush is not being overlooked; a life-test is indicated here. Also, the effect of the mercury on the container with time should be examined. In this connection the addition of a slight amount of titanium or zirconium to mercury is said to completely inhibit its attack on steel. Also, a better wetting of the steel surface by the mercury is claimed to be effected by the presence of a tiny amount of magnesium. These and other facts about mercury appear in Appendix B as excerpts from Ref. 3. Some of the physical properties of mercury are given in Table XVIII.

CONCLUSIONS

The word "conclusion" carries with it too final a ring for this experiment as thus far conducted. Perhaps some opinion can be expressed.

1. A mercury brush is a satisfactory device electrically at sea level.
2. The voltage drop induced by current flow across a moving mercury-steel contact is independent of current density and speed of contact.

RECOMMENDATIONS

These recommendations could concern only those who might be interested in pursuing the project further along similar lines.

1. The "disc" should be fixed and only the "cylinder" rotate.

2. Some sort of variable-speed drive up to 12,000 rpm would be useful.

3. The cylinder diameter should be increased progressively to permit investigation up to an absolute maximum peripheral speed.

4. The use of the liquid conductor brush on an actval machine would serve to eliminate the carbon brushes.

5. Drive shaft size should be kept large enough to obviate heat generation due to current flow in it.

6. It would be desirable to build into the device some sort of plastic window to permit visual observation of the phenomena occurring.

7. The means of picking off the voltage drop across the brush should be improved.

8. The effect of varying the gap length shorted by the liquid conductor should be investigated.

9. The effect of varying the contact area (current density) needs further investigation.

10. The liquid conductor container should be seamless in the region where the fluid will circulate during rotation.

11. An effective seal against leakage about the "disc" shaft is an essential.

12. The test data to be taken should be given careful consideration and every test identically conducted.

13 A life-test of the device should be conducted after which a critical examination of the contact surfaces and the fluid conductor should be made.

REFERENCES

1. A thesis by LT R. E. Morris, USN, listing the high-altitude carbon brush problems, U.S. Naval Postgraduate School, June 1952.
2. Noeggerath, J.S.: Acyclic (Homopolar) Dynamos, Proceedings of A.I.E.E., Vol. XXIV, January 1905, Page 19.
3. Liquid Metals Handbook, NavExos P-733, 1 June 1950, Atomic Energy Commission, Department of the Navy, Washington, D. C.

TABLES

ILLUSTRATIONS

APPENDIX

TABLE I

RESULTS OF TEST NO. 5

Start Test No. 5 @ 1400; Stop @ 1430

RPM, disc. 900

RPM, cylinder. 600

Speed, relative,f.p.s. . 15

Ambient temp, °C 29

Date . . . . . . .15 May 1952

Brush Current, Amperes	Carbon Current Density Amp/In^2	Mercury Current Density Amp/In^2	Total Brush Drop Volts	Carbon Brush Drop Volts	Mercury Brush Drop Volts	* Elapsed Time, Minutes	Disc Temp Rise °C	Cylinder Temp. Rise °C
4	4.26	.65	2.35	1.89	.46	5	7	8
8	8.52	1.31	2.75	2.31	.44	7	8	10
12	12.78	1.96	2.80	2.36	.44	9	9	12
16	17.04	2.52	2.90	2.40	.50	12	9	14
20	21.33	3.27	3.10	2.64	.46	14	13	17
24	25.56	3.93	3.10	2.58	.52	17	14	21
28	29.82	4.58	3.20	2.66	.54	19	17	25
32	34.08	5.24	3.30	2.73	.57	21	19	31
36	38.34	5.89	3.40	2.84	.56	22	22	36
40	42.66	6.55	3.45	2.85	.60	23	25	40
44	46.86	7.20	3.60	2.99	.61	24	29	44
48	51.15	7.85	3.80	3.17	.63	25	32	49
48	51.15	7.85	3.75	3.09	.66	30	#49	#69

*Approximated on basis of later timed tests.

#Temperature stabilized.

TABLE II

RESULTS OF TEST NO. 6

Start Test No. 6 @ 1445; Stop @ 1515.

RPM, disc. 1300

RPM, cylinder. 700

Speed, relative,fps. . . 20

Ambient temp, °C 30

Date. . . . . . . .15 May 1952

Brush Current, Amperes	Carbon Current Density Amp/In^2	Mercury Current Density Amp/In^2	Total Brush Drop, Volts	Carbon Brush Drop, Volts	Mercury Brush Drop, Volts	* Elapsed Time, Minutes	Disc Temp Rise °C	Cylinder Temp. Rise °C
5	5.33	.82	2.35	2.03	.32	5	17	13
10	10.66	1.64	2.65	2.30	.35	8	17	13
15	16.00	2.46	2.80	2.46	.34	11	17	15
20	21.33	3.27	3.10	3.08	.32	14	18	20
25	26.66	4.09	3.15	2.80	.35	17	19	23
30	32.00	4.91	3.20	2.88	.32	19	21	26
35	37.33	5.73	3.20	2.82	.38	21	23	30
40	42.66	6.55	3.35	2.97	.38	23	25	33
45	48.00	7.36	3.45	3.05	.40	24	28	39
48	51.15	7.85	3.60	3.22	.38	25	31	44
48	51.15	7.85	3.80	3.36	.44	30	#45	#63

*Approximated on basis of later timed tests.

#Temperature stabilized.

TABLE III

RESULTS OF TEST NO. 7

Start Test No. 7 @ 1530; Stop at 1550

RPM, disc. 1300
RPM, cylinder. . . .1200
Speed, relative,
f.p.s. 25.5
Ambient temp. oC . .30
Date. . . . .15 May 1952

Brush Current, Amperes	Carbon Current Density, Amp/In²	Mercury Current Density, Amp/In²	Total Brush Drop, Volts	Carbon Brush Drop, Volts	Mercury Brush Drop, Volts	Elapsed Time, Minutes	Disc Temp Rise oC	Cylinder Temp. Rise oC
5	5.33	.82	2.50	2.10	.40	1	15	13
10	10.66	1.64	2.90	2.44	.46	2	15	13
15	16.00	2.46	2.95	2.63	.32	3	16	15
20	21.33	3.27	2.95	2.62	.33	4	17	19
25	26.66	4.09	3.15	2.81	.34	5	19	23
30	32.00	4.91	3.25	2.89	.36	6	20	27
35	37.33	5.73	3.35	2.97	.38	7	23	30
40	42.66	6.55	3.60	3.20	.40	8	26	39
45	48.00	7.36	3.80	3.38	.42	12	32	47
48	51.15	7.85	3.95	3.31	.64	15	34	49
48	51.15	7.85	4.00	3.36	.64	20	#44	#61

*Approximated on basis of later timed tests.

#Temperature stabilized.

TABLE IV

RESULTS OF TEST NO. 8

Start Test No. 8 @ 1430; Stop @ 1510

RPM, disc. 1500
RPM, cylinder. 1500
Speed, relative, f.p.s. . . . 31
Ambient temp., °C. 27
Date. . . . . .16 May 1952

Brush Current Amperes	Carbon Current Density, Amp/In^2	Mercury Current Density Amp/In^2	Total Brush Drop, Volts	Carbon Brush Drop, Volts	Mercury Brush Drop, Volts	* Elapsed Time, Minutes	Disc Temp Rise °C	Cylinder Temp. Rise °C
5	5.33	.82	2.25	1.75	.50	13	25	27
10	10.66	1.64	2.90	2.37	.53	15	23	28
15	16.00	2.46	3.15	2.61	.54	17	23	28
20	21.33	3.27	3.30	2.72	.58	19	24	31
25	26.66	4.09	3.40	2.78	.62	21	26	33
30	32.00	4.91	3.60	2.97	.63	23	28	40
35	37.33	5.73	3.70	3.04	.66	25	31	44
40	42.66	6.55	3.80	3.12	.68	28	34	49
45	48.00	7.36	3.85	3.17	.68	30	38	55
48	51.15	7.85	4.00	3.30	.70	32	42	60
48	51.15	7.85	4.00	3.30	.70	40	#53	#73

*Approximated on basis of later timed tests.

#Temperature stabilized.

TABLE V

RESULTS OF TEST NO. 9

Start Test No. 9 @ 1530; Stop @ 1550

RPM, disc. 1800
RPM, cylinder. 1700
Speed, relative, f.p.s. . . . 36
Ambient temp, °C 27
Date. . . . . .16 May 1952

Brush Current, Amperes	Carbon Current Density Amp/In^2	Mercury Current Density Amp/In^2	Total Brush Drop Volts	Carbon Brush Drop, Volts	Mercury Brush Drop, Volts	* Elapsed Time, Minutes	Disc Temp Rise °C	Cylinder Temp Rise °C
5	5.33	.82	2.40	1.94	.46	1	23	20
10	10.66	1.64	2.90	2.36	.54	2	24	22
15	16.00	2.46	3.05	2.51	.54	3	25	25
20	21.33	3.27	3.25	2.65	.60	4	26	28
25	26.66	4.09	3.40	2.78	.62	5	29	34
30	32.00	4.91	3.55	2.92	.63	6	33	43
35	37.33	5.73	3.65	2.97	.68	7	35	47
40	42.66	6.55	3.80	3.12	.68	9	39	51
45	48.00	7.36	4.00	3.28	.72	11	43	57
48	51.15	7.85	4.00	3.28	.72	13	47	62
48	51.15	7.85	3.85	3.15	.70	20	#55	#73

*Approximated on basis of later timed tests.

#Temperature stabilized.

Table VI

RESULTS OF TEST NO. 10

Start Test No. 10 @ 1030; stop @ 1051

RPM, disc. 2000
RPM, cylinder. 2000
Speed, relative, f.p.s. . . . 41
Ambient temp., °C 27
Date. . . . . .19 May 1952

Brush Current, Amperes	Carbon Current Density, Amp/In^2	Mercury Current Density, Amp/In^2	Total Brush Drop, Volts	Carbon Brush Drop, Volts	Mercury Brush Drop, Volts	* Elapsed Time, Minutes	Disc Temp Rise °C	Cylinder Temp Rise °C
5	5.33	.82	2.75	2.24	.51	1	23	20
10	10.66	1.64	3.15	2.62	.53	2	25	23
15	16.00	2.46	3.35	2.77	.58	3	26	26
20	21.33	3.27	3.45	2.87	.58	4	27	30
25	26.66	4.09	3.60	2.98	.62	5	29	35
30	32.00	4.91	3.65	3.01	.64	7	33	42
35	37.33	5.73	3.70	3.06	.64	9	36	46
40	42.66	6.55	3.90	3.20	.70	11	40	50
45	48.00	7.36	4.00	3.27	.73	13	43	56
48	51.15	7.85	4.00	3.27	.73	15	47	63
48	51.15	7.85	4.00	3.27	.73	21	#57	#73

*Approximated on basis of later timed tests.

#Temperature stabilized.

TABLE VII

RESULTS OF TEST NO. 11

Start *Test No. 11 @ 1117; Stop @ 1142

RPM, disc. 2250
RPM, cylinder. 2250
Speed, relative, f.p.s 46.5
Ambient temp., oC 27
Date . . . . 19 May 1952

Brush Current, Amperes	Carbon Current Density, Amp/In^2	Mercury Current Density, Amp/In^2	Total Brush Drop, Volts	Carbon Brush Drop, Volts	Mercury Brush Drop, Volts	Elapsed Time, Minutes	Disc Temp Rise oC	Cylinder Temp Rise oC
5	5.33	.82	2.80	2.22	.58	1	27	22
10	10.66	1.64	3.20	2.60	.60	4	28	24
15	16.00	2.46	3.30	2.68	.62	5	29	26
20	21.33	3.27	3.35	2.72	.63	6	29	27
25	26.66	4.09	3.50	2.85	.65	8	31	32
30	32.00	4.91	3.65	2.97	.68	9	32	37
35	37.33	5.73	3.80	3.11	.69	11	33	42
40	42.66	6.55	3.80	3.09	.71	12	35	47
45	48.00	7.36	4.00	3.28	.72	13	37	52
48	51.15	7.85	4.00	3.27	.73	15	40	57
48	51.15	7.85	4.05	3.35	.70	25	#44	#69

*For Test No. 11 and subsequent tests, an 18" fan was directed on the cylinder from a distance of about 12". Estimate blast at 1" to 2" of water.

#Temperature stabilized.

TABLE VIII

RESULTS OF TEST NO. 12

Start Test No. 12 @ 1155; Stop @ 1218

RPM, disc. 2500
RPM, cylinder. 2500
Speed, relative, f.p.s 51
Ambient temp., °C 27
Date. . . . . .19 May 1952

Brush Current, Amperes	Carbon Current Density, Amp/In^2	Mercury Current Density, Amp/In^2	Total Brush Drop, Volts	Carbon Brush Drop, Volts	Mercury Brush Drop, Volts	Elapsed Time, Minutes	Disc Temp Rise °C	Cylinder Temp Rise °C
5	5.33	.82	2.75	2.16	.59	1	33	24
10	10.66	1.64	3.00	2.40	.60	2	34	24
15	16.00	2.46	3.10	2.48	.62	3	35	26
20	21.33	3.27	3.15	2.52	.63	5	36	29
25	26.66	4.09	3.20	2.55	.65	7	38	31
30	32.00	4.91	3.30	2.62	.68	9	39	36
35	37.33	5.73	3.75	3.05	.70	10	40	40
40	42.66	6.55	3.85	3.15	.70	12	42	46
45	48.00	7.36	4.00	3.28	.72	14	43	53
48	51.15	7.85	4.10	3.36	.74	15	45	58
48	51.15	7.85	4.15	3.47	.68	23	#49	#72

#Temperature stabilized.

TABLE IX

RESULTS OF TEST NO. 13

Start Test No. 13 @ 1425; stop @ 1447

RPM, disc. 2750
RPM, cylinder. 2750
Speed, relative, f.p.s . . . 57
Ambient temp., ^{o}C. 27
Date. . . . . .19 May 1952

Brush Current, Amperes	Carbon Current Density, Amp/In^2	Mercury Current Density, Amp/In^2	Total Brush Drop, Volts	Carbon Brush Drop, Volts	Mercury Brush Drop, Volts	Elapsed Time, Minutes	Disc Temp Rise oC	Cylinder Temp Rise oC
5	5.33	.82	2.30	1.75	.55	1	36	20
10	10.66	1.64	2.55	1.95	.60	2	36	22
15	16.00	2.46	2.90	2.26	.64	4	36	26
20	21.33	3.27	3.20	2.52	.68	5	36	28
25	26.66	4.09	3.40	2.70	.70	6	38	31
30	32.00	4.91	3.45	2.75	.70	9	41	38
35	37.33	5.73	3.65	2.93	.72	10	42	41
40	42.66	6.55	3.70	2.97	.73	12	43	45
45	48.00	7.36	3.85	3.10	.75	13	45	51
48	51.15	7.85	3.90	3.13	.77	15	47	56
48	51.15	7.85	4.15	3.39	.76	22	#52	#68

#Temperature stabilized.

TABLE X

RESULTS OF TEST NO. 14

Start Test No. 14 @ 1524; Stop @ 1551

RPM, disc. 3000
RPM, cylinder. 3000
Speed, relative, f.p.s 62
Ambient temp., °C. 30
Date. . . . . 19 May 1952

Brush Current, Amperes	Carbon Current Density, Amp/In^2	Mercury Current Density, Amp/In^2	Total Brush Drop, Volts	Carbon Brush Drop, Volts	Mercury Brush Drop, Volts	Elapsed Time, Minutes	Disc Temp Rise °C	Cylinder Temp Rise °C
5	5.33	.82	2.80	2.23	.57	1	48	15
5	5.33	.82	2.90	2.27	.63	9	45	20
10	10.66	1.64	3.15	2.52	.65	10	45	22
15	16.00	2.46	3.25	2.60	.68	12	46	23
20	21.33	3.27	3.50	2.82	.70	14	47	25
25	26.66	4.09	3.80	3.10	.72	16	48	33
30	32.00	4.91	3.90	3.18	.73	17	49	37
35	37.33	5.73	4.00	3.27	.74	18	50	40
40	42.66	6.55	4.20	3.46	.77	20	51	45
45	48.00	7.36	4.40	3.63	.78	21	53	50
48	51.15	7.85	4.50	3.72	.77	22	55	57
48	51.15	7.85	4.45	3.68		27	#58	#66

#Temperature stabilized.

TABLE XI

RESULTS OF TESTS NO. 15 & 16

Start Test No. 15 @ 1600; Stop @ 1611

RPM, disc. 3250
RPM, cylinder. 3250
Speed, relative, f.p.s. . . . 67
Ambient temp., ^oC. 30
Date. . . . . .19 May 1952

Brush Current, Amperes	Carbon Current Density, Amp/In^2	Mercury Current Density, Amp/In^2	Total Brush Drop, Volts	Carbon Brush Drop, Volts	Mercury Brush Drop, Volts	Elapsed Time, Minutes	Disc Temp Rise ^oC	Cylinder Temp Rise ^oC
48	51.15	7.85	4.30	3.55	.75	3	#64	54
48	51.15	7.85	4.50	3.75	.75	9	#67	64
48	51.15	7.85	4.50	3.75	.75	11	#70	66

Start Test No. 16 @ 1020; Stop @ 1032

RPM, disc. 3500
rpm, cylinder. 3500
Speed, relative, f.p.s. . . . 72
Ambient temp, ^oC 25
Date. . . . . .21 May 1952

48	51.15	7.85	4.30	3.55	.75	6	57	61
48	51.15	7.85	4.30	3.55	.75	7	60	65
48	51.15	7.85	4.45	3.69	.76	8	62	69
48	51.15	7.85	4.40	3.63	.77	9	64	70
48	51.15	7.85	4.25	3.47	.78	10	66	71
48	51.15	7.85	4.30	3.52	.78	11	67	72
48	51.15	7.85	4.40	3.62	.78	12	69	73

#Suspect this excessive rise due to binding seal.

TABLE XII

RESULTS OF TESTS NO. 17,18 & 19

Brush Current, Amperes	Carbon Current Density Amp/In^2	Mercury Current Density, Amp/In^2	Total Brush Drop, Volts	Carbon Brush Drop, Volts	Mercury Brush Drop, Volts	Elapsed Time, Minutes	Disc Temp Rise oC	Cylinder Temp Rise oC

Test No. 17

RPM, disc. 3750
RPM, cylinder. 3750
Speed, relative,f.p.s. . 77.5
Ambient temp., oC. . . . 25
Date. . . . . .21 May 1952

48	51.15	7.85	4.40	3.65	.75	*10	#57	43
1	1.07	.16	--	--	.50	1	---	--

Test No. 18[1]

RPM, disc. 1500
RPM, cylinder. 1500
Speed, relative,f.p.s. . 31
Ambient temp., oC. . . . 25
Date. . . . . .21 May 1952

48	51.15	7.85	4.00	3.50	.50	*10	#47	25

[2]**Test No. 19**

RPM, disc. 4000
RPM, cylinder. 4000
Speed, relative,f.p.s. . 83
Ambient temp., oC. . . . 30
Date. . . . . . .23 May 1952

48	51.15	7.85	5.00	4.22	.78	5	#70	60
1	1.07	.16	----	----	.50	1	---	--

[1]Continuation Test No. 17 wherein RPM reduced abruptly.

[2]Reversed polarity; made disc (+); also reduced carbon brush pressure to minimum.

*Estimated

#Due to binding seal.

Brush Current, Amperes | Carbon Current Density, Amp/In² | Mercury Current Density, Amp/In² | Volts

Test No. 17

48 51.15 7.85
1 1.07 .15

Test No. 18

48 51.15

[2]Test No.

48 51.15
1 1.07 .15

[1]Continuation Test No. 17

[2]Reversed polarity ... brush pressure ...

*Estimated

#Due to ...

TABLE XIII

RESULTS OF TEST NO. 20

Start Test No. 20 @ 1120; stop @ 1230

RPM, disc. 4000
RPM, cylinder. 4000
Speed, relative, f.p.s. . . 83
Ambient temp., ^{o}C. 25
Date. . . . . .26 May 1952

Brush Current, Amperes	Carbon Current Density, Amp/In^2	Mercury Current Density, Amp/In^2	Total Brush Drop, Volts	Carbon Brush Drop, Volts	Mercury Brush Drop, Volts	Elapsed Time, Minutes	Disc Temp Rise ^{o}C	Cylinder Temp Rise ^{o}C
48	51.15	13.20	5.60	5.00	.60	14	57	63
			5.65	5.03	.62	15	59	63
			5.65	5.03	.62	16	60	62
			5.60	4.98	.62	18	60	65
			5.60	4.92	.68	21	60	66
			5.60	4.88	.72	24	60	67
			5.65	4.95	.70	26	60	68
			5.50	4.78	.72	29	60	70
			5.40	4.80	.60	30	59	70
			5.40	4.80	.60	31	59	70
			5.60	4.92	.68	33	57	70
			5.40	4.76	.64	39	58	72
			5.25	4.61	.64	41	57	71
			5.20	4.42	.78	43	57	71
			5.40	4.80	.60	45	57	71
48	51.15	13.20	5.50	4.86	.64	46	57	71
5	5.33	1.38	2.50	2.12	.38	47	53	67
			3.20	2.74	.46	49	47	52
			3.20	2.70	.50	51	42	40
			3.40	2.95	.45	53	39	33
			3.40	2.97	.43	56	37	29
			3.60	3.10	.50	58	37	27
			3.50	3.00	.50	60	38	26
5	5.33	1.38	3.45	2.95	.50	63	38	26
0	0	0	0	0	0	66	39	24
0	0	0	0	0	0	70	38	24

TABLE XIV

RESULT OF TEST NO. 21

Start Test No. 21 @ 1325; Stop @ 1425

RPM, disc. 5125
RPM, cylinder. 5225
Speed, relative,f.p.s. . . . 107
Ambient temp., °C. 25
Date. . . . . .26 May 1952

Brush Current Amperes,	Carbon Current Density, Amp/In^2	Mercury Current Density Amp/In^2	Total Brush Drop Volts	Carbon Brush Drop, Volts	Mercury Brush Drop, Volts	Elapsed Time, Minutes	Disc Temp. Rise °C	Cylinder Temp. Rise °C
0	0	0	0	0	0	5	42	15
						8	49	16
						10	38	16
						11	49	16
0	0	0	0	0	0	12	49	16
5	5.33	3.45	4.30	3.82	.48	13	49	19
5	5.33	3.45	4.40	3.92	.48	16	50	19
25	26.66	17.20	5.25	4.59	.66	17	52	25
			5.25	4.63	.62	19	54	32
			5.35	4.73	.62	21	55	37
			5.40	4.78	.62	23	54	38
			5.40	4.79	.61	25	54	40
			5.50	4.86	.64	28	54	41
			5.50	4.82	.68	30	54	42
			5.50	4.80	.70	33	53	43
			5.50	4.80	.70	33	53	43
25	26.66	17.20	5.50	4.83	.67	35	52	43
48	51.15	33.10	6.25	5.52	.73	36	55	47
48	51.15	33.10	6.05	5.32	.73	37	58	53
48	51.15	33.10	6.05	5.34	.71	38	59	59
48	51.15	33.10	6.00	5.30	.70	39	61	61
48	51.15	33.10	5.80	5.12	.68	40	62	66
48	51.15	33.10	5.85	5.15	.70	42	62	68
48	51.15	33.10	5.80	5.13	.67	43	62	69
48	51.15	33.10	5.80	5.20	.60	45	62	71
48	51.15	33.10	6.00	5.42	.58	47	62	72
48	51.15	33.10	6.00	5.40	.60	50	63	73
25	26.66	17.20	5.30	4.70	.60	51	61	70
25	26.66	17.20	5.50	4.87	.63	52	58	69
25	26.66	17.20	5.60	5.05	.55	53	58	60
5	5.33	3.45	3.95	3.43	.52	54	55	53
5	5.33	3.45	4.30	3.80	.50	56	53	45
5	5.33	3.45	4.65	4.00	.65	57	53	40
0	0	0	0	0	0	58	52	35
0	0	0	0	0	0	60	52	33

TABLE XV

RESULTS OF TESTS NO. ~~23~~ 22, 23

Started Test No. 22 @ 1433; stop @ 1453

RPM, disc. 3000
RPM, cylinder. 3000
Speed, relative, f.p.s. . . 62
Ambient temp., °C. 25
Date. . . . . .26 May 1952

Brush Current, Amperes	Carbon Current Density, Amp/In^2	Mercury Current Density, Amp/In^2 ①	Total Brush Drop, Volts	Carbon Brush Drop Volts	Mercury Brush Drop Volts	Elapsed Time Minutes	Disc Temp Rise °C	Cylinder Temp Rise °C
48	51.15	33.10	5.60	5.25	.35	1	37	30
48	51.15	33.10	4.50	4.18	.32	3	37	30
48	51.15	33.10	4.60	4.20	.40	10	40	63
48	51.15	33.10	5.50	5.12	.38	13	43	67
25	26.66	17.20	----	----	.26	15	40	65
25	26.66	17.20	4.50	4.15	.35	19	40	50
5	5.33	3.45	2.70	2.65	#.05	20	--	--

①Density probably much greater, as open-ckt developed shortly after Test 22.

Started Test No. 23 @ 1542; Stop @ 1606
Date, RPM, Ambient Same as Test No. 22

Brush Current, Amperes	Carbon Current Density, Amp/In^2	Mercury Current Density, Amp/In^2	Total Brush Drop, Volts	Carbon Brush Drop Volts	Mercury Brush Drop Volts	Elapsed Time Minutes	Disc Temp Rise °C	Cylinder Temp Rise °C
48	51.15	13.20	5.40	4.80	.60	1	25	48
			5.40	4.70	.70	4	33	53
			5.70	5.00	.70	6	35	58
			5.50	4.80	.70	8	37	61
			5.40	4.70	.70	10	39	62
			5.40	4.70	.70	12	40	63
48	51.15	13.20	5.50	4.80	.70	14	40	63
48	51.15	13.20	----	----	---	18	40	*--
5	5.33	1.38	3.00	2.40	.60	20	35	--
5	5.33	1.38	3.10	2.55	.55	22	28	--
5	5.33	1.38	3.40	2.85	.55	24	23	--

#This low reading no mistake; current was varied 0 to 50 and reading repeated.

*At this point, cylinder thermometer vibrated out of shaft and was bent.

SUMMARY OF TESTS No. 20, 21, 22 & 23

TABLE XVI

Brush Current Amps.	Hg Current Density Amp/In^2	Rel. Spd. F.P.S.	Hg Volt Drop	Test Number
48	13.2	83	.66	20
5	1.38	83	.48	20
5	3.45	107	.52	21
25	17.2	107	.63	21
48	33.1	107	.67	21
48	33.1	62	.36	22
25	17.2	62	.30	22
5	3.45	62	.05	22
48	13.2	62	.69	23
5	1.38	62	.57	23

NOTE: Column 4 is an average over a "steady-state" period.

TABLE XVII

TEMPERATURE RISE SUMMARY OF ALL TESTS

Brush Curr. Amps.	Rel. Spd. F.P.S.	Aver. Temp. Rdgs. °C	Test No.	Brush Curr. Amps.	Rel. Spd. F.P.S.	Aver. Temp. Rdgs. °C	Test No.	Brush Curr. Amps.	Rel. Spd. FPS	Aver. Temp. Rdgs. °C	Test No.
5	20	15	6	5	46.5	25	11	5	83	32	20
25	20	21	6	25		32		48		64	
48	20	54	6	48		56		0		31	
5	25.5	14	7	5	51	28	12	0	107	32	21
25	25.5	21	7	25		35		5		34	
48	25.5	53	7	48		60		25		48	
								48		68	
5	31	26	8	5	57	28	13				
25		30	8	25		35		48	62	52	23
48		63	8	48		60					
5	36	21	9	5	62	32	14				
25		32		25		40					
48		64		48		62					
5	41	22	10	48	67	68	15				
25		32									
48		65		48	72	71	16				

TABLE XVIII

SOME PHYSICAL PROPERTIES

OF

MERCURY, IRON, COPPER

	Hg.	Fe	Cu
Atomic Weight	200.61	55.84	63.57
Density, gm. per cc.	13.546	7.87	8.89
Melting Point, °C	-38.87	1535	1083
Latent Heat of Fusion, g-Cal per g.	2.776	65	49.3
Boiling Point, °C	356.9	3200	2300
Latent Heat of Vaporization, g-cal per g.	71	1110	1756
Specific heat, Btu per lb.	.0333	.1075	.0928
Thermal Coeff. of Linear Expansion, x 10^4 per °C	#	.119	.162
Thermal Cond., g-cal/sec/ cm^2/°C/cm	.0148	.18	.918
Electrical Resistivity, ohm cm cube	95.783	9.8	1.724
Temp Coeff of Resistivity	.00089	.0065	.00393

$\frac{1}{v}\frac{dv}{dt} = 182 \times 10^{-6}$ @ 20°C

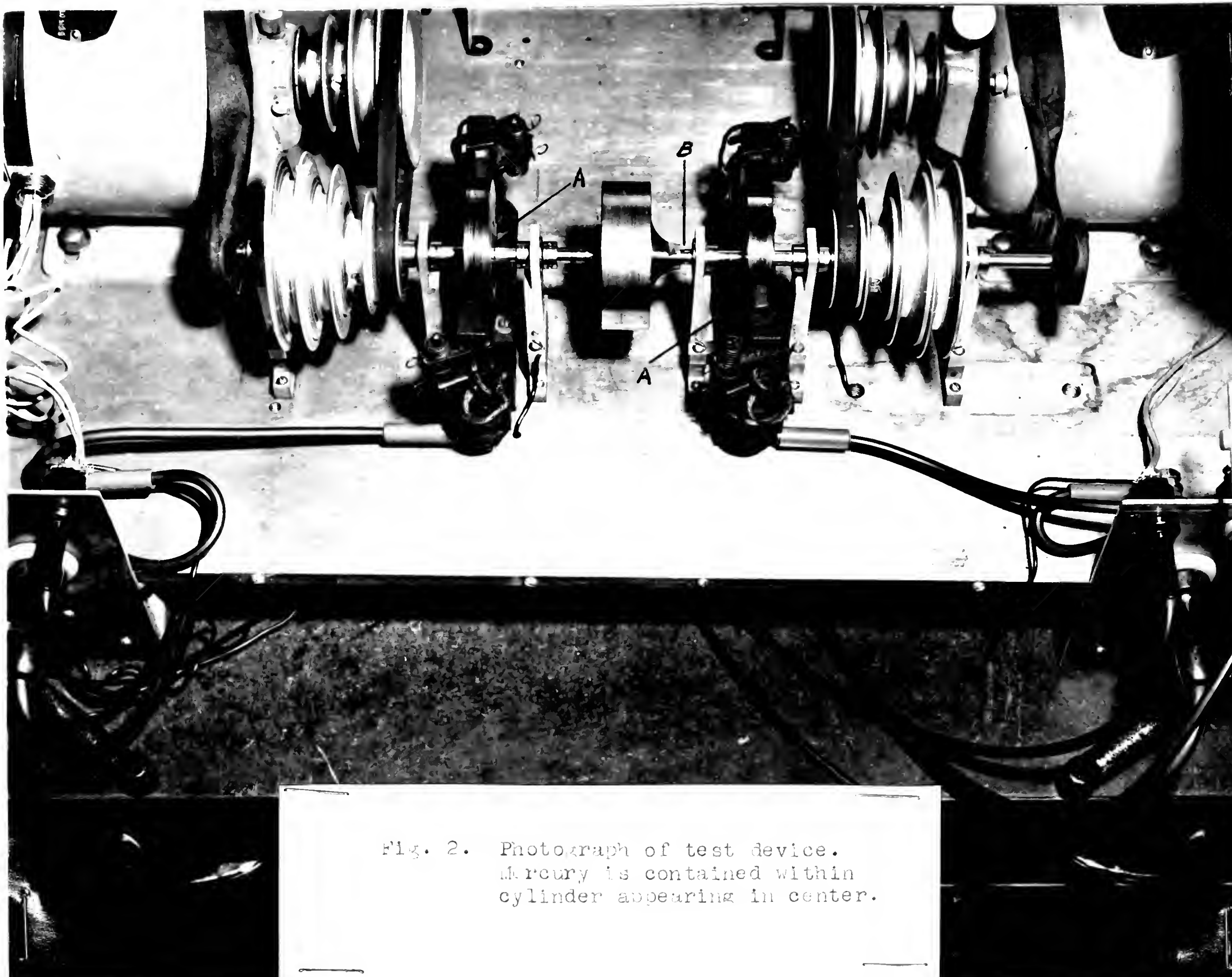


Fig. 2. Photograph of test device. Mercury is contained within cylinder appearing in center.

Fig. 3. Front view of complete test apparatus.

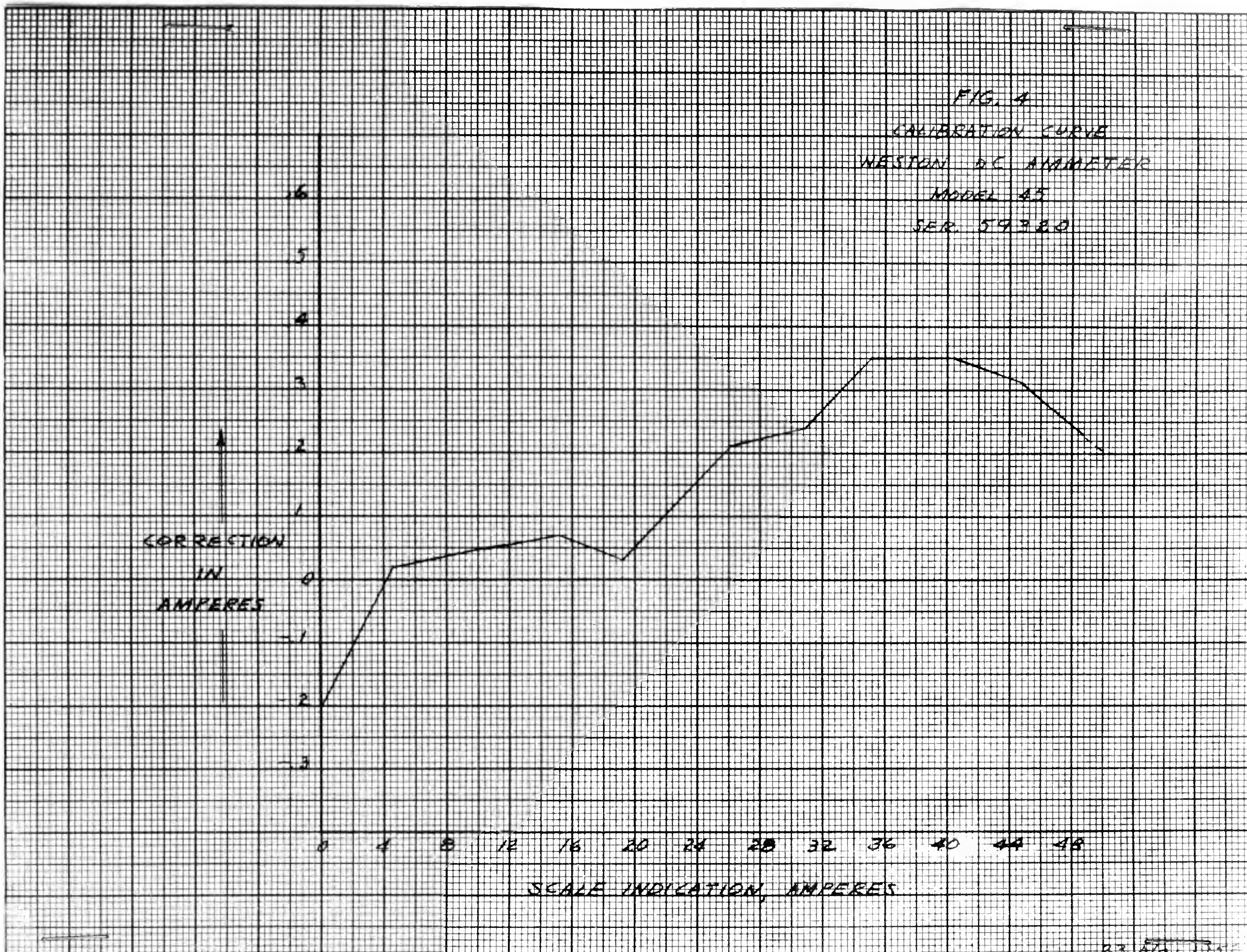


FIG. 4
CALIBRATION CURVE
WESTON DC AMMETER
MODEL 45
SER. 59320
CORRECTION IN AMPERES
SCALE INDICATION, AMPERES
0
4
8
12
16
20
24
28
32
36
40
44
48
6
5
4
3
2
1
0
-1
-2
-3

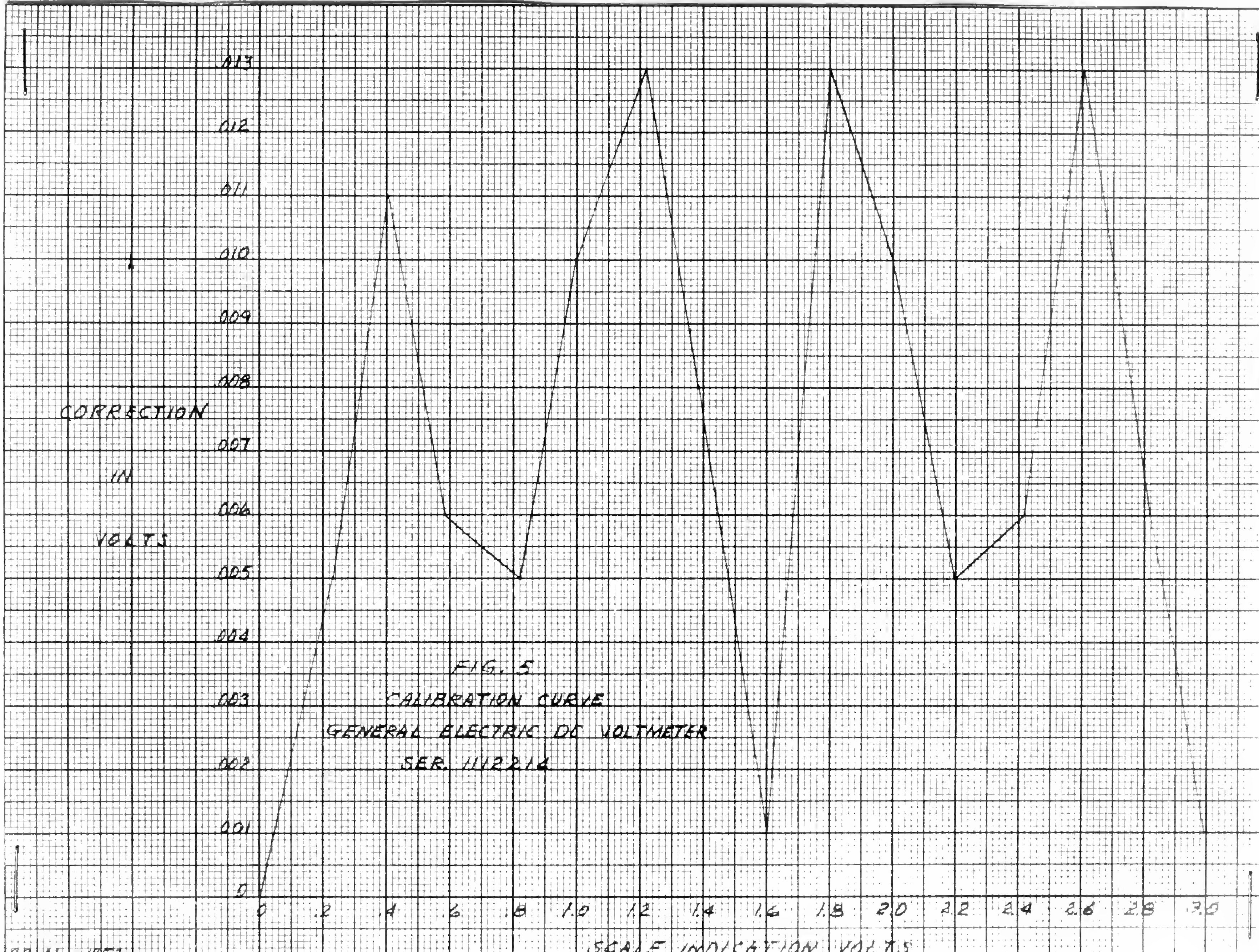


FIG. 5
CALIBRATION CURVE
GENERAL ELECTRIC DC VOLTMETER
SER. 1112214

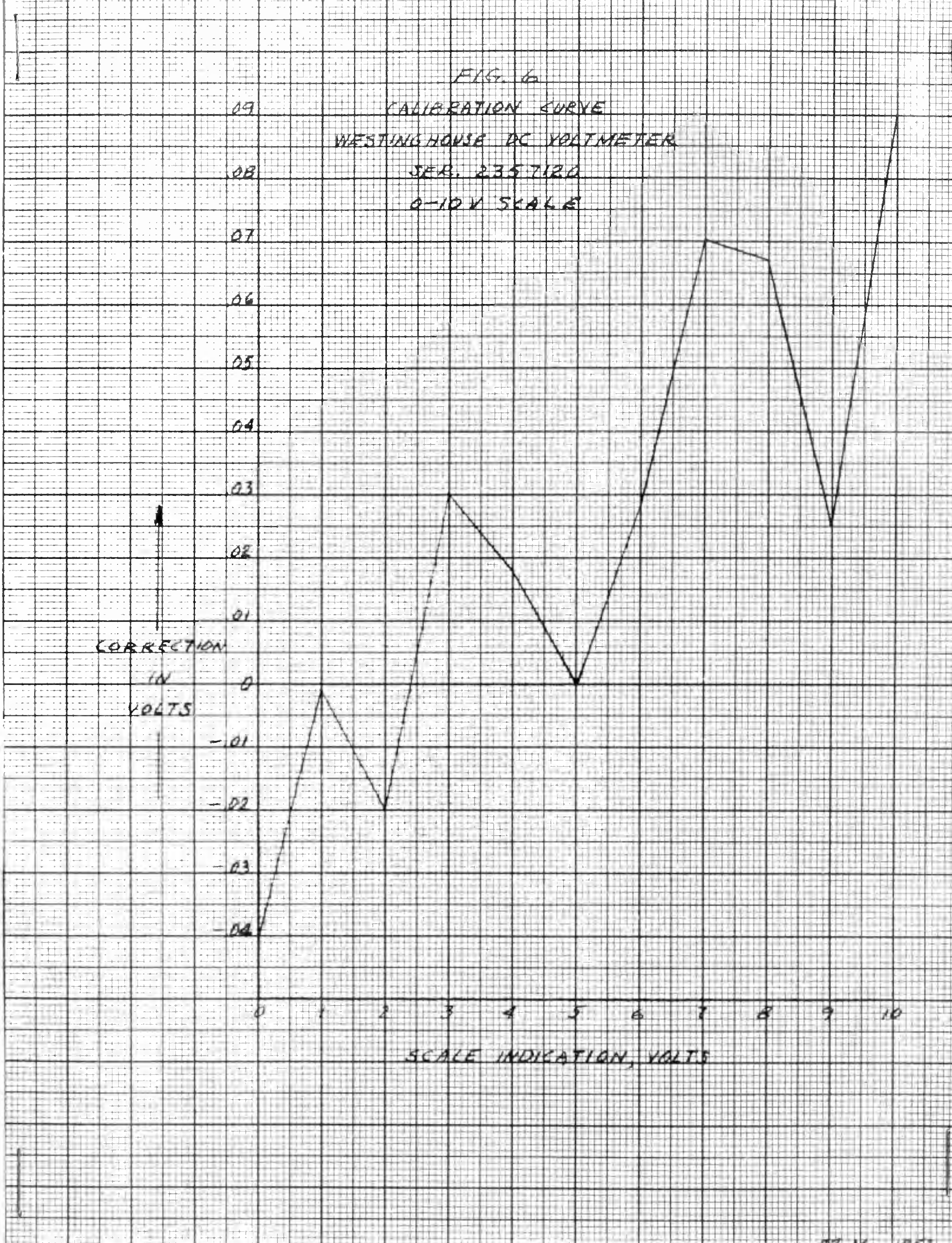


FIG. 6
CALIBRATION CURVE
WESTINGHOUSE DC VOLTMETER
SER. 2357120
0-10 V SCALE

Fig. 7. Left side view of apparatus.

Fig. 8. Right side view of apparatus.

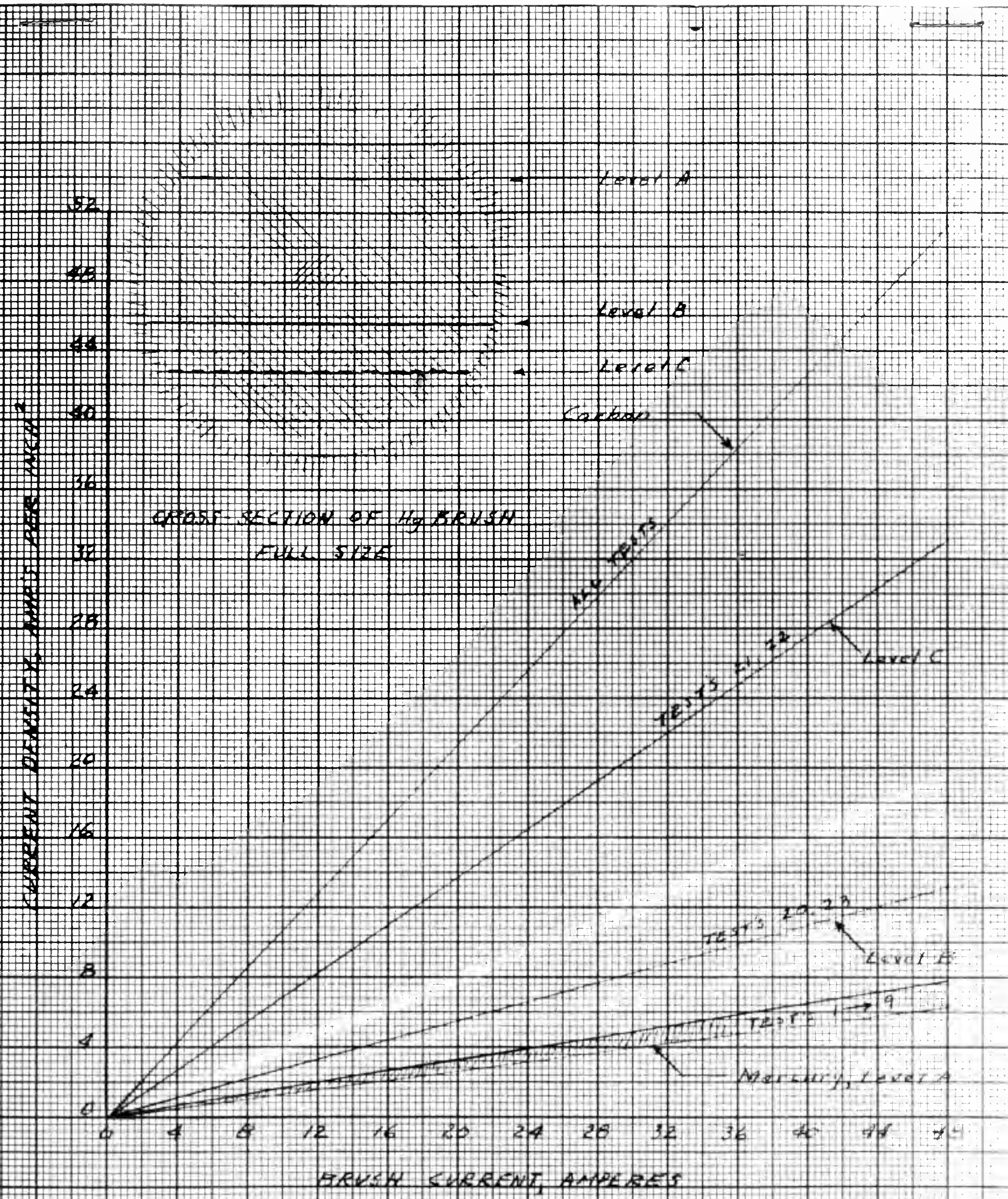


FIG. 9. CURVE OF CURRENT DENSITIES

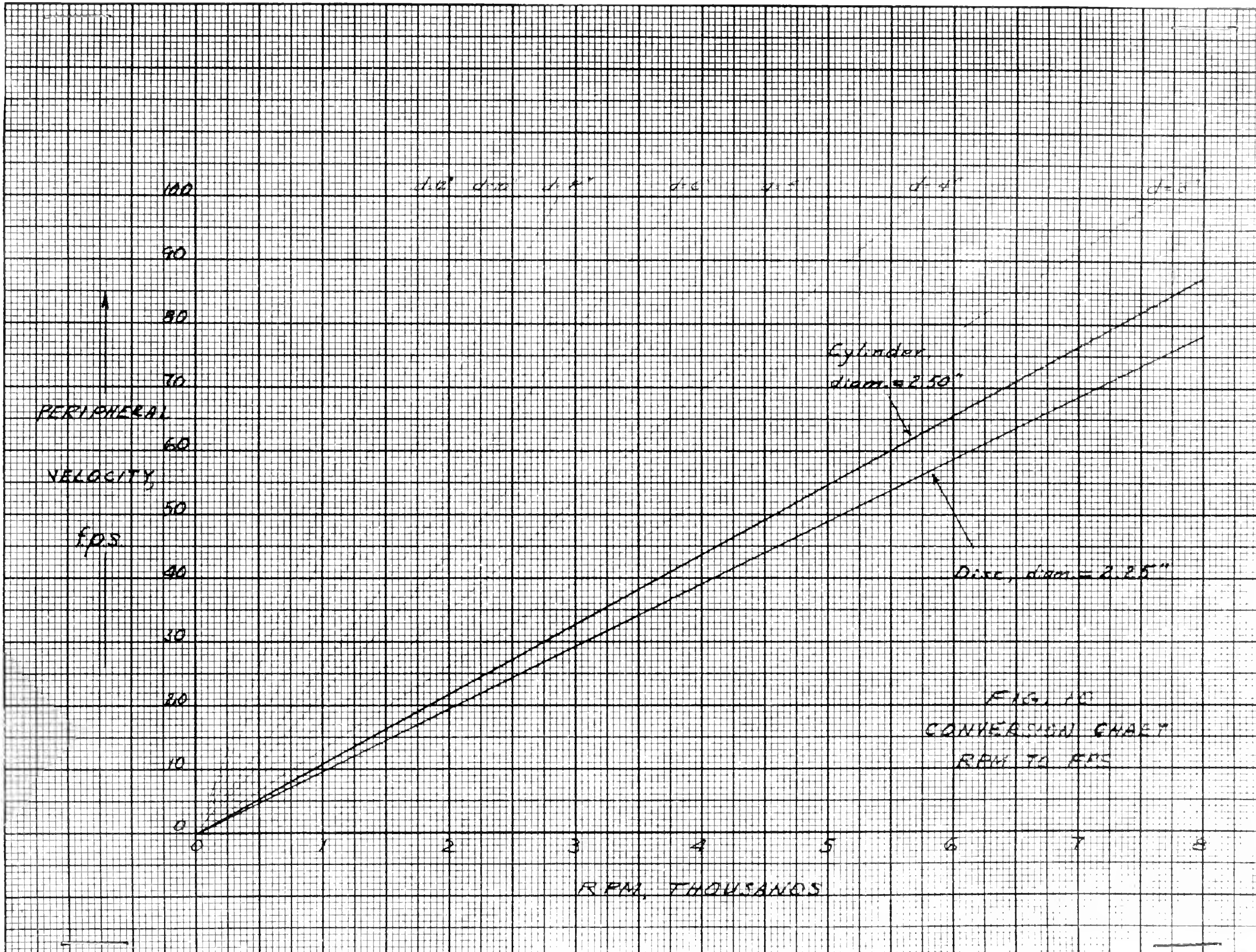


FIG. 10
CONVERSION CHART
RPM TO FPS

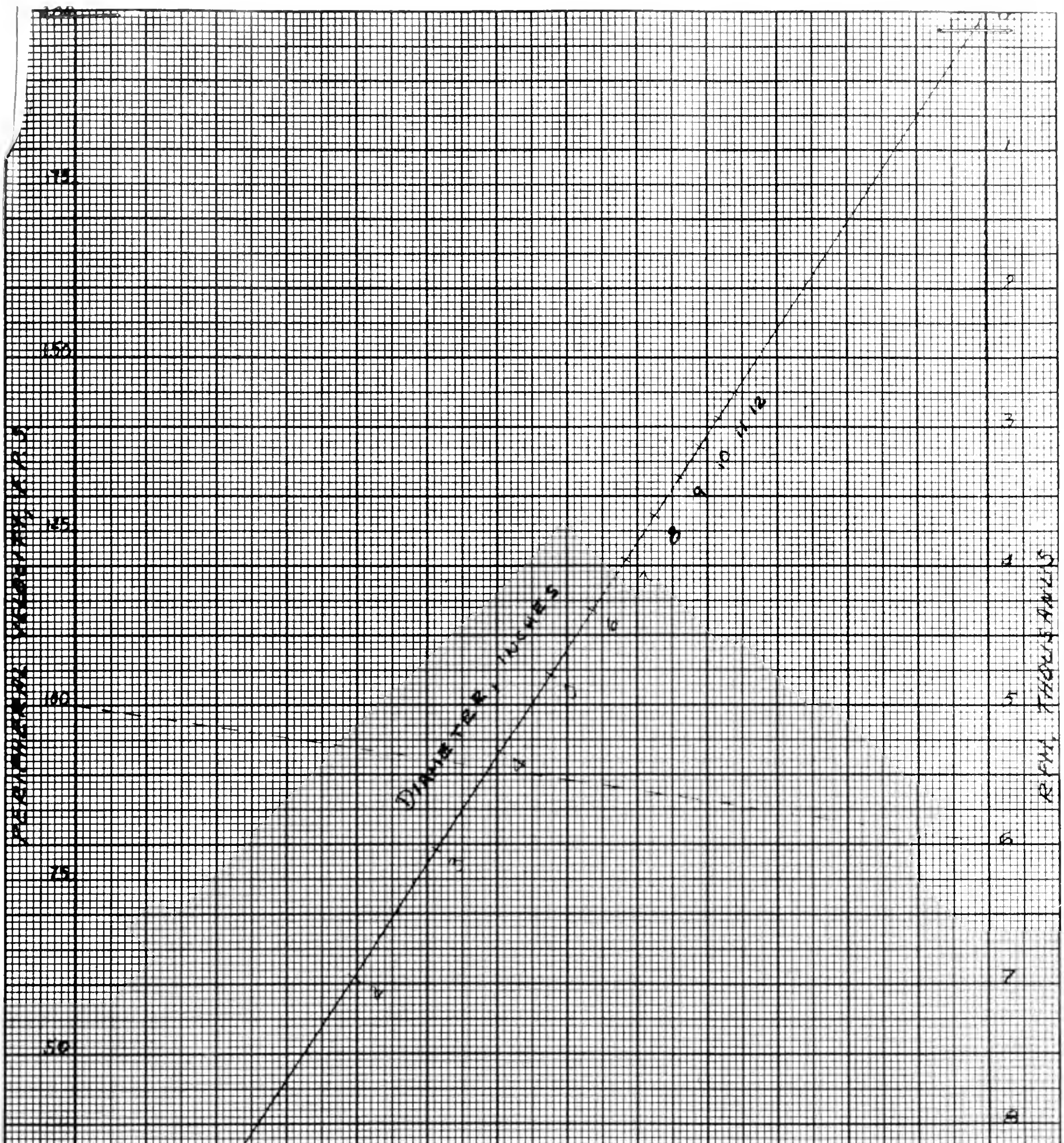


FIG. 11. CONVERSION CHART, RPM TO FPS.

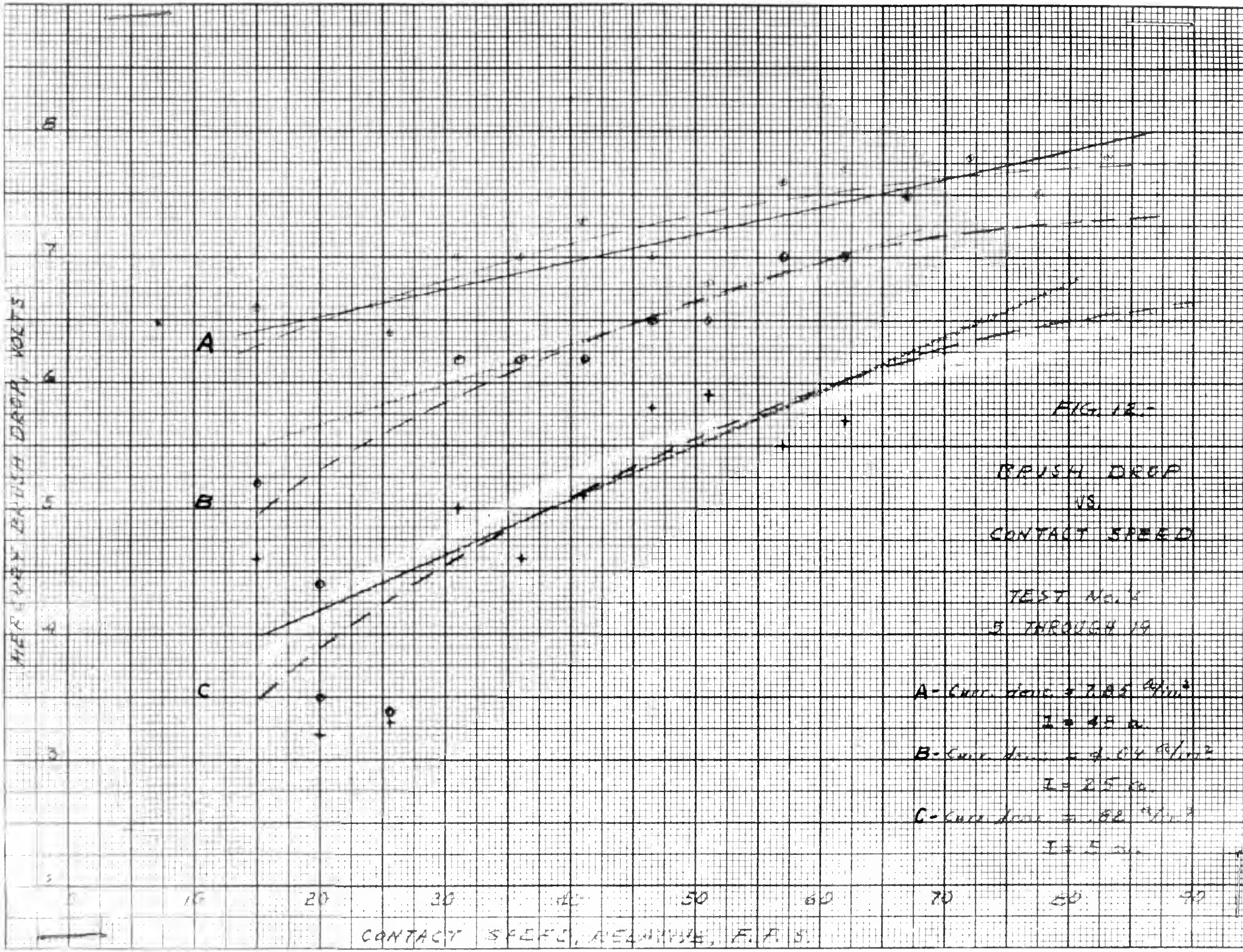
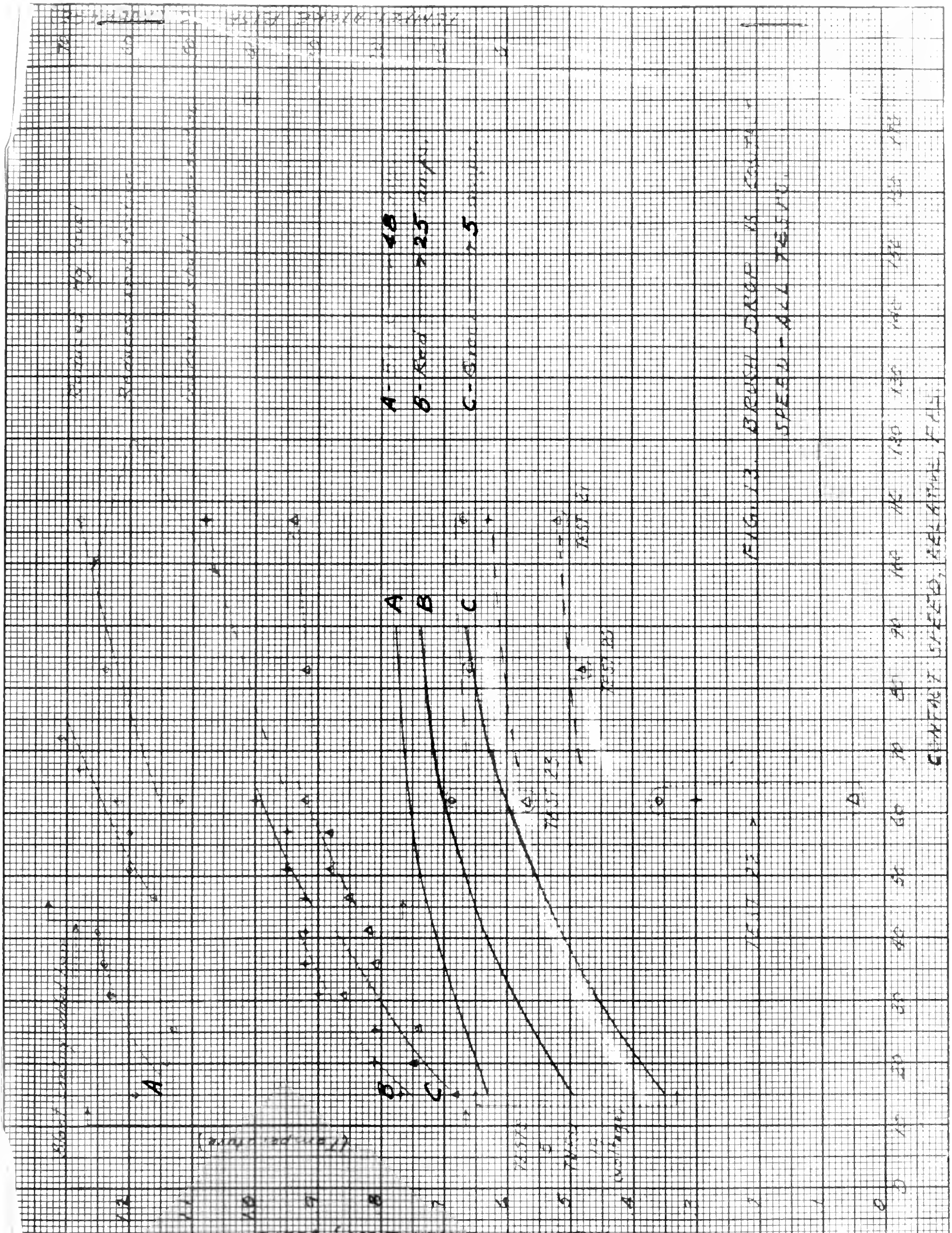
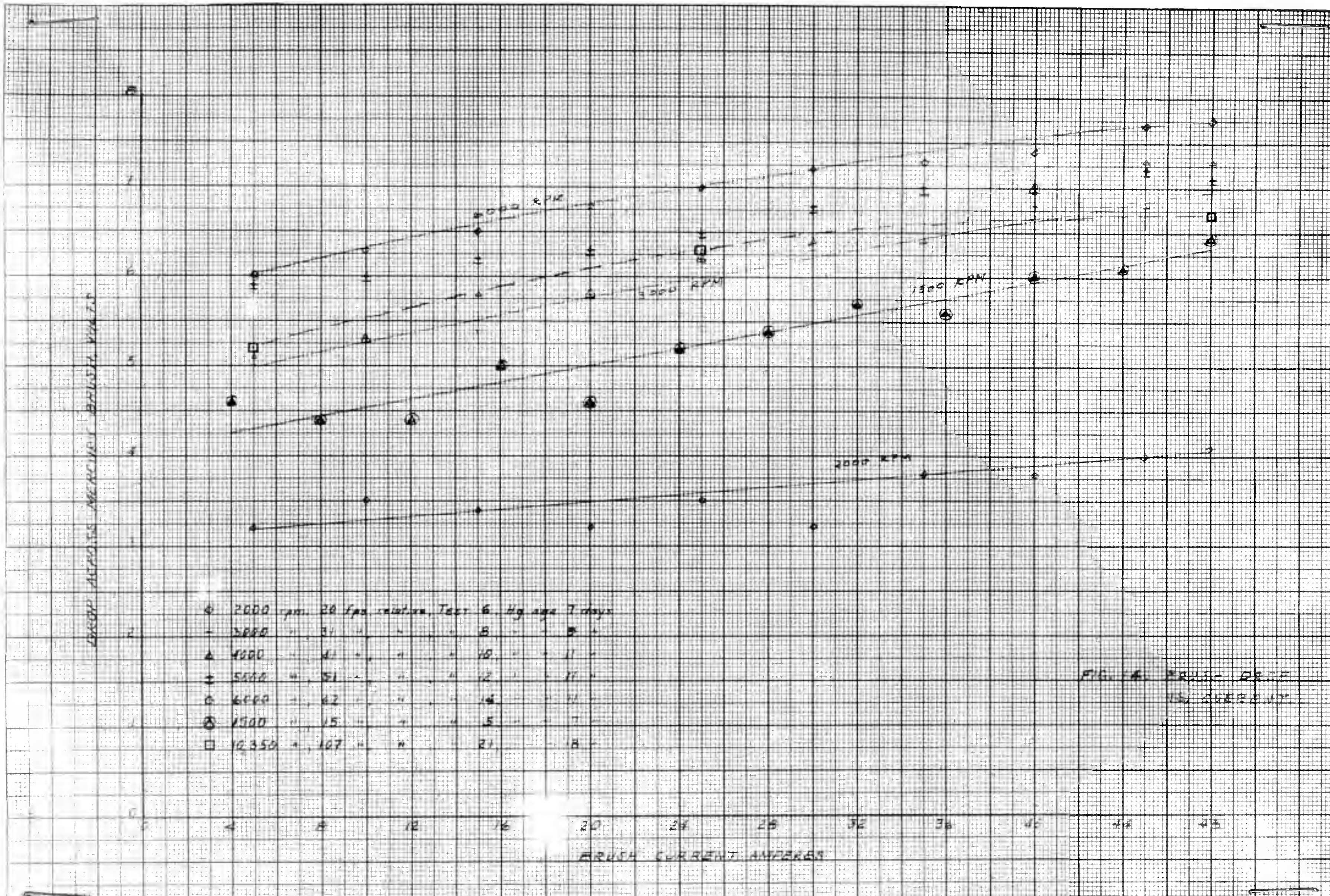
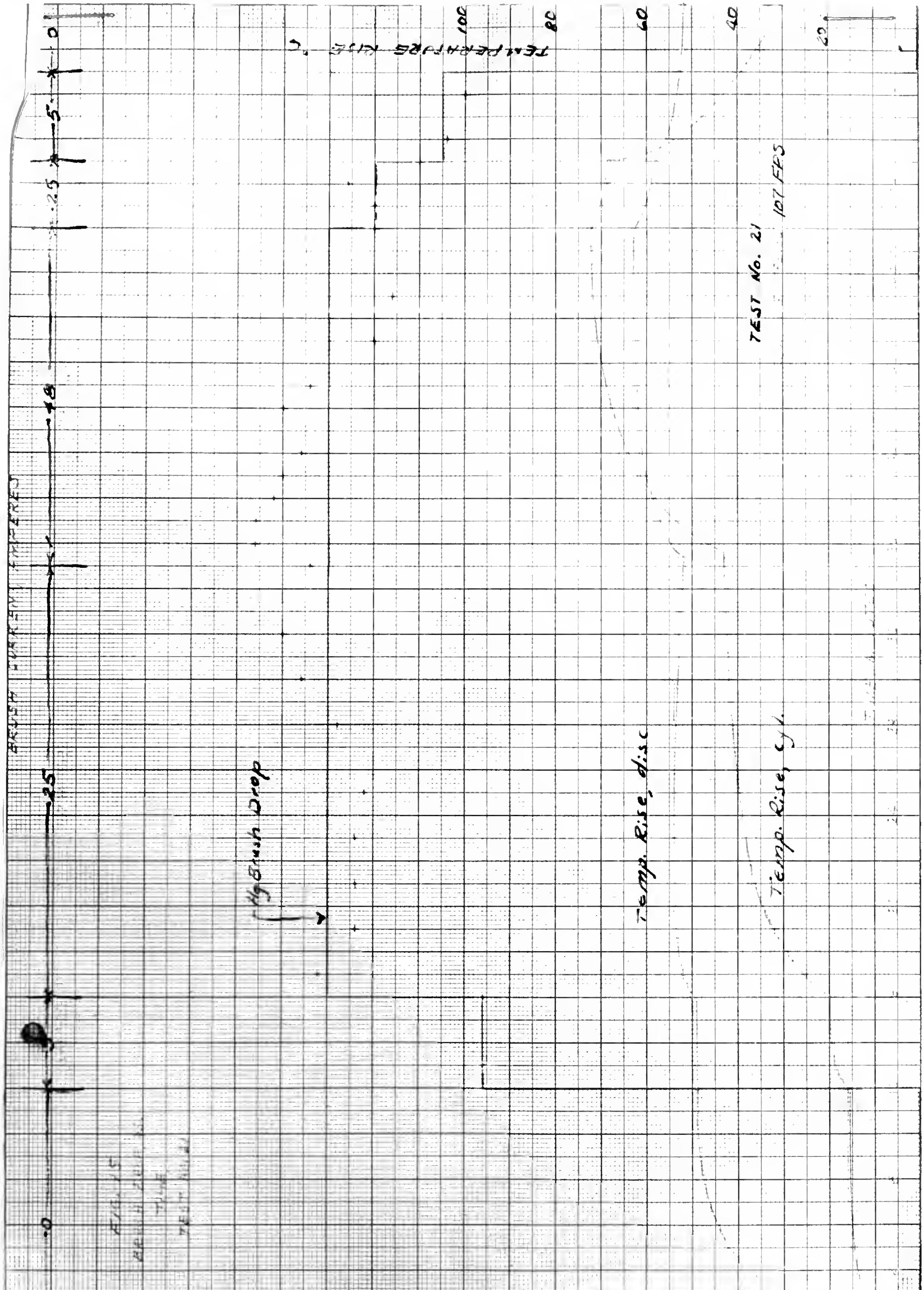


FIG. 12.-
BRUSH DROP
VS.
CONTACT SPEED
TEST No. 5
5 THROUGH 19
A- Curr. dens. = 7.85 A/in.²
I = 48 a.
B- Curr. dens. = 4.04 A/in.²
I = 25 a.
C- Curr. dens. = .82 A/in.²
I = 5 a.
A
B
C
MERCURY BRUSH DROP, VOLTS
CONTACT SPEED, RELATIVE, F.P.S.


MERCURY BRUSH DROP, VOLTS
(Temperature)
CONTACT SPEED, RELATIVE, FPS
A
B
C
TEST 23
TEST 23
TEST 25
TEST 27
A - 48
B - Red 25 amps.
C - 5 amps.
FIG. 13. BRUSH DROP VS CONTACT SPEED - ALL TESTS.


2000 rpm. 20 fps relative, Test 6, Hg age 7 days
3000 " 31 " " " 8 " " 8 "
4000 " 41 " " " 10 " " 11 "
5000 " 51 " " " 12 " " 11 "
6000 " 62 " " " 14 " " 11 "
1500 " 15 " " " 5 " " 7 "
10,350 " 107 " " " 21 " " 18 "
2000 RPM
3000 RPM
1500 RPM
2000 RPM
DROP ACROSS MERCURY BRUSH VOLTS
BRUSH CURRENT AMPERES
FIG. 14. BRUSH- DROP VS. CURRENT


TEST No. 21
107 FPS
Hg Brush Drop
Temp. Rise, disc
Temp. Rise, cyl.

APPENDIX A

LABORATORY LOG

[illegible]

[illegible]

22 APRIL 1952

Finally got down to work on thesis project at about 1415 p.m. Disassembled, cleaned and oiled. Fitted the carbon brushes to the brass slip rings. Required the help of Joe Octavek to open the cylinder in order that preservative oil could be cleaned out. Noted DČ motors are shunt wound. Will have to exercise care that field doesn't open inadvertently.

For power will have to start up synchronous motor, DC generator set.

23 APRIL 1952

Cleaned oil out of conducting cylinder. Re-aligned and tightened entire mechanism. Mounted 2 armature slide-wire rheostats and 2 field slide-wire rheostats. Next plan to connect and test DC motors; be sure to uncouple v-belts. In testing for grounds, noted one v-belt shows less than infinite (500k) resistance. Re-check on 7 May showed infinite R both belts.

24 April 1952

Installed terminal lugs, connected motors. Started up AC-DC set and tested motors. Both run satisfactorily. Next plan to test rotary brush assembly for alignment and heat (temp.) rise.

25 APRIL 1952

Started the mechanism on slowest possible speed (motors on smallest pulleys) and noted temperature rises. Cylinder end stabilized at about 400-500 C, whereas disc end tended

to overheat (60°-80°C). After a run-in of 30-40 minutes, disc end steadied at about 60°C. Next set motors on largest pulleys. Without extreme care in speed control, it was possible to rapidly and easily overheat the disc end. Trouble was at mercury seal, a pressed paper sleeve (journal) bearing on the disc shaft (and rotating with the cylinder). Temperature of disc end went as high as 160°C; cylinder end steady at about 50°C. Permitted speeds such that disc end ran at about 100°-120°C for 30-40 minutes. Noted small amount bearing grease on paper seal was of great help. Secured device, packed small quantity grease about paper seal in hope sufficient absorption would take place to permit cooler running. Necessary that device run cool in order to avoid danger of flashing mercury into vapor. To this extent, must remember to provide a ventilating blower once mercury is placed in cylinder.

30 APRIL 1952

Started device. Temperatures both ends steady at about 45°-50°C., even at relative speed of 12,000 rpm. Connected and adjusted two strobotacs. Connected adjustable load resistor bank (1-72 amps) to provide current control for rotating brush. Connected ammeter and voltmeter to record current through brush and drops across carbon and Hg together and across Hg alone.

To provide for maximum control of speed and current, started up another M-G set. One set provided voltage for driving motors; other set providing voltage for load

resistor bank. In this way, have two speed controls: (1) field rheostat on DC generator; (2) armature and field rheostats in DC motors. Also then have two current controls: (1) field rheostat on second DC generator; (2) rotary switch on load bank (parallel connected).

Load bank is good for 72 amps. (Go to 48 amps.)

Started up both M-G sets; brought motors up to speed (about 4,000 rpm each); shorted out rotating brush (since as yet no mercury in it); and put about 6 amps through carbon brush assembly. Noted voltmeters as connected to read from pedestal-to-pedestal would give no readings. Investigation showed grease on bearings sufficient to act as insulator. In probing with ohmmeter, noted resistance of rotating brush had dropped from about 500 kΩ (prior to greasing seal) to 26 k Ω. This of no consequence, particularly since mercury when added will drop resistance to very low value, anyway.

With the 6 amps (about) through the carbon brushes with the cylinder and disc shorted out, noted about a 4-volt drop across the carbon brushes. This would be the drop across all four brush sets in series.

At this point there was a main power failure on the station. Secured for the day. It does appear there will be a problem in determining the drop across the mercury brush alone.

During actual conduct of test with mercury, carbon, brush drop will be that of only two brushes.

1 MAY 1952

Installed voltage probes, ~~as shown by sketch on Page 36~~. Some adjustment appears necessary: voltage fluctuates ± .2v. May be due to carbon brush irregularities. Still have not used mercury, although obtained 5# jug of Hg and funnel and gradvate from Professor Reynolds of Chemistry Department.

Device ran satisfactorily--was on only 10-15 minutes. Ran current up to about 12 amps; brass slip rings may develop a squeal and they seemed to get quite hot for such a short run.

Believe voltage probes will be satisfactory. Next plan to run in carbon brushes for an hour or so.

2 MAY 1952

Voltage probes proved unsatisfactory; marked tendency to cut into shaft.

3 MAY 1952

Tried brass spring leaf bearing on brass slip ring. Might be satisfactory if spring leaves were longer; riding on edge (side) of slip rings, there is too much relative velocity. Electrician's Mate 1/C Hull suggested use of twin-brush recorder to permit comparison voltage fluctuations due to carbon brushes and those due to brass spring leaf contacts. Set up brush apparatus but did not have time to make it function properly.

There is a fair amount of random voltage fluctuation across the carbon brushes; there is even more across the brass springs. At this point it appears steady voltages will not be attainable. Possibly a better fit of the carbon brushes will reduce the fluctuations.

7 MAY 1952

Removed stiff brass voltage pickoffs and replaced with longer, less-stiff, brass spring leaf pickoffs. Made it possible to reduce relative velocity at point contact by moving this point closer to center of rotation. Still, however, had voltage fluctuations $\pm .4$ volt on a 2-volt max. Sanded contacts and brass slip-ring. Also re-sanded one set of carbon brushes. Not much effect.

Decided to fill contact race with carbon smudge from the slip-ring--there was an immediate reduction to negligible proportions of the voltage swing about a stable value. This stability resulted for both voltages: that taken from the slip-ring and that taken across the entire carbon brush assembly in series. With the arrangement for the brush run-in (all four sets in series), the voltmeter on the slip-rings was reading the drop across the two center sets of the series. It should have, therefore, read ½ the voltage across the entire set, which it did to a reasonable degree. A maximum current of about 10-12 amperes was put through the four carbon brush sets in series for about two hours. It was observed that the brush drop was largely independent of current and somewhat of speed, rising somewhat

with speed. It was also observed that the driving motors slowed down when current through the brushes was reduced or interrupted, coming quickly up to original speed when current was again turned on. The effect was an immedicate and easily noticeable one.

The device was run up to about 6,000 rpm on each end for several minutes at a time. It is believed alignment, lubrication, stability, control, rigidity, temperature rise are now satisfactory for actual test runs with mercury.

The fluid brush shunt was removed; strobotacs, voltmeters, ammeter, etc. were made ready. Next plan to add mercury and record data. Be sure to provide two ventilating fans.

8 MAY 1952

Poured 10 cc. of Hg into cylinder. Measured resistance (about 30 ohms). Started rotation, relative velocities up to several thousand rpm. Resistance variable, but very much greater than 30 ohms. It appeared after several minutes of rotation that the resistance was almost that of an open circuit. After several minutes of rotation, although the shaft thermometers were steady at about 45°C, the cylinder was almost too hot to touch.

On the idea that there was insufficient area of contact due to rotation holding the Hg on the inside periphery of the cylinder and away from the disc, 5.5 cc. more of Hg were added to the cylinder. This dropped the static re-

sistance to about 20 ohms, but appeared to have no effect in reducing the dynamic resistance. Again, high heat was noted on the cylinder perimeter with cool shafts.

It is possible there was enough oil film in the cylinder to cause an insulating effect. (There was no cleaning fluid available in the lab upon assembly to remove all oil.) It is possible there will be slight amalgamation with time, sufficient to break down the high resistance effect. It is also possible that introduction of a fairly heavy current through the brush will reduce the high resistance.

It was noted that the cylinder motor came up to speed much more easily with the disc motor off, indicating a good deal of friction between the low carbon steel and the mercury.

No leaks were noted. Cylinder was secured with filler plug down to test for leaks overnight.

Next plan to shift pulleys such that can have very low rpm on disc and cylinder--possibly introduce current next time.

9 MAY 1952

No Hg leakage overnight. Shifted to low speed pulleys. Static resistance about 25 ohms. Ran the device, turned brush current on. Used varying amounts of current up to 12 amps. Carbon brush drop fairly steady at about 2-2.5 volts; mercury drop steady--.15-.5 (fluctuates). Stopped device, measured static resistance (about 2 ohms). Upon letting machine set idle for 10-15 minutes, static

resistance built back up to 25 ohms. There is an immediate drop in resistance once current is turned on and the resistance is variable such that the voltage drop is constant and independent of current. Voltmeter fluctuations are believed to be caused by imperfect voltage pick-offs and carbon brush contacts. Plan next to take data.

12 MAY 1952

Some Hg leakage, 1 drop, due to loose pressed paper insert between disc shaft and cylinder. Tightened two hold-on screws; (should have had four or more of these screws.) Estimate now have about 15.5, (.3, .4) cc. Hg in cylinder.

Measured static resistance, 16 ohms. Ran device without current; measured static resistance again, 3.5 ohms. Device still exhibits immediate resistance drop when current turned on; voltage drop still independent of current.

Took data, listed as Test No. 1. The "average" column is not necessarily the arithmetic average of the maximum and minimum readings, but is rather the value at which the needle appeared to want to indicate. Each reading consumed about 5 minutes in order to permit something approaching "steady-state."

14 MAY 1952

Ran tests No. 2 through 4. Brush current up to 48 amperes; relative rpm up to 1400.

15 MAY 1952

Ran tests No. 5 through 7. Current up to 48 amps;

relative rpm up to 2500. Voltage drop across carbon and mercury remain largely independent of current but shows slight increase (.2 volt) as the temperature rises to 100°C. One hundred degrees C. has been taken as an arbitrary upper limit since this temperature is being read at the center of the Hg brush, whereas the hot-spot seems to be on the cylinder periphery. Care is being taken to avoid flashing the mercury into poisonous vapor which would occur if the Hg temperature were to rise to 357°C, STP. All bearings run cool to the touch. The brass slip rings are too hot to touch, as is the cylinder.

16 MAY 1952

Ran Tests No. 8 and 9, (48 amps, 3500 rpm). Limited to 48 amps by current density of carbon brushes. Carbon brush contact surface is

$$4 \times \frac{5}{16} \times \frac{3}{4} = \frac{60}{64} \text{ in.}^2 \; ; \quad \frac{48 \text{ amps}}{60/64} = 50 \text{ amps/in.}^2$$

Actually, I believe mercury can carry much greater currents with proper cooling provided. Have not computed Hg current density, but believe it to have reached only some 5 to 10 amps/in.^{2}

17 MAY 1952

Conducted no formal tests, but ran device at about 3,000 rpm, relative and 5 amps from about 1030 steadily until 1630 (6 hrs.) as part of Armed Forces Day exhibit.

Temperature cylinder about 55°C.; discs, 60°C; carbon voltage about 3.2v; Hg voltage about 0.5 v all day. Both voltages steady.

19 MAY 1952

One drop of Hg leakage. Estimate 15 cc. Hg still in cylinder. Static resistance equals 40 Ω ; dynamic R = 5Ω. Ohmmeter Weston Model 665, type 3, Serial 041058. Ambient 27°C.

Ran tests No. 10 through 15. Noted disc end becoming quite hot and noted in connection with it that pressed paper insert around shaft at cylinder (mercury seal) seemed to be binding on shaft. Again used up to 48 amps, rpm up to 6,000 with 6,500 rpm for a short duration. Greased seal again.

Also noted cylinder slinging Hg through threaded joint, apparently as a result of heat expansion and centrifugal force at 3,000 rpm. Estimate 14.5 cc. of Hg remaining in cylinder.

Indications are that tests should possibly be at test rpm and maximum current (48 amps) from a cold start with ~~them~~ then a temperature-time curve taken to estimate how close to temperature stability device is approaching before one or other of thermometers reach 100°C.

20 MAY 1952

Started device; temperature on disc end jumped to 70°C. Packed grease about pressed paper seal. Secured after a 5-minute run. No leakage apparent. Static resistance on order of 20-40 ohms; ohm meter appeared unstable.

21 MAY 1952

Ran tests No. 16, 17, 18. One drop leakage. Where greasing was of some help, effect quickly wore off at 3500 rpm and disc end again began to show excessive temperature. Repacked seal with grease.

22 MAY 1952

Assisted Prof. Polk in calibrating voltmeters used to obtain carbon and mercury drops; meters very good.

23 MAY 1952

Ran Test No. 19. First assisted Prof. Polk in calibrating ammeter used to obtain brush current; both accurate to high degree.

Reversed polarity on brush; i.e., made disc (+), cylinder (-). Also reduced carbon brush pressure to the minimum. Drive belts appear to be showing effect of wear. Still have binding at pressed-paper insert causing excessive heating.

24, 25 MAY 1952

Reducing data, drawing curves, computing.

Calculated minimum Hg contact surface; found it to be 6.11 in.^{2} compared to only 15/16 in.^{2} for carbon. Maximum Hg density (48 amps) = 7.85 amp/in.^{2} compared to 51.15 amp/in.^{2} for carbon. Conclu~~sions~~de have been ultra-conservative. Calculations suggest removal of Hg to point just where no leakage can occur on the shaft opening,--the less Hg, the less heat due to friction.

In this connection, also remove paper insert and cut off its flange since ~~it~~ will have no leakage problem, except that seeping through threaded joint. Also solder a bead about the open threads at the shaft side of the cylinder. The combination of drilled core and threads have reduced shaft c/s area at this point to the extent where a hot-spot develops at currents above 40 amps.

Believe above three steps may make possible 10,000 or 12,000 rpm without excessive heating. Also, since load bank will handle 72 amps and DC generator is rated at 59 amps (110v), believe can go to highest available current.

<u>26 MAY 1952</u>

Cut down seal but had to add back some tape to stop Hg slinging. Reduced mercury level to 1 7/32" (1 15/64") above bottom of cylinder exterior. RPM 4,000 each end with no excessive heating. Put solder bead about exposed threads on shaft at cylinder.

Next try reducing Hg level to bottom of exterior seal. Amounts to a reduction of 2cc. from above.

Threw out enough Hg in running @ 10,000 rpm to place Hg level at bottom of seal exterior by coincidence. Prior to shutting down after Test 22 noted Hg drop as low as .05v with 5 amps, 3,000 rpm each end.

In then attempting to go to 6,000 rpm on each end, encountered excessive vibration and Hg slinging to point where open-circuit developed across mercury brush. Re-filled cylinder to 1 15/64" above bottom of cylinder exterior, and conducted Test No. 23.

At 1600, thermometer in cylinder shaft (tape) came loose and was bent. Straightened; have next to test this thermometer for accuracy in any future tests.

Stopped driving motors; allowed 5 amps. to flow; drop across Hg brush fluctuated 0.4v to 1.1v.

Perhaps possible to conclude mercury is satisfactory as an electrical brush at high rpm (peripheral velocities) if the amount of Hg is kept to a minimum. Course now suggested is to weld threaded joint and to add four more screws or so on seal to obviate any leakage, then fill to Hg level used in 10,000 rpm test. (Hg level 7/8" above bottom exterior of cylinder) and then run device at maximum current (48 or 59 amps) for 1,000 hours or until failure. At this point, remove weld, disassemble, examine for condition of surfaces and of Hg and also amount of Hg left. If still satisfactory, reseal and reweld and run for 1,000 more hours in an altitude chamber.

APPENDIX B

Excerpts From Liquid Metals Handbook

Ref: <u>Liquid</u> <u>Metals</u> <u>Handbook</u>, NavExos P-733, 1 June 1950, Atomic Energy Commission, Department of the Navy, Washington, D. C. For sale by Superintendent of Documents, U.S. Government Printing Office, Washington, D. C. $1.25

Page 2: "The pressure created by passing an electric current through a molten metal, in combination with a magnetic field, offers a solution to the problem of pumping these metals." (i.e., molten $A\ell$, Zn, Cu, etc.) Pumping head only 1 to 2 feet (p. 5).

Page 5: The present (1950) uses of liquid metals do not list electric current conduction through a moving contact.

Page 9: Hg boiler tubes are made from Sicromo 5S steel (0.12 C, 0.5 Mo, 5.0 Cr, 1.5 Si) which has a very low solubility in Hg. The use of .000005 to .001 per cent titanium and .002 per cent Mg in the Hg assures that Hg wets steel and reduces solubility of tube metal (950°-1050° F). 18-8 stainless also good.

Page 11: "A pipe filled with Na was used as a bus bar for carrying 4000 amps of DC current by Dow Chemical CO." (See Boundy, R. H., Trans. Electrochen. Soc. 62, 151 (1932), Sodium Bus Bar--A 4000 amps. cond. "Liquid metals are successfully used as 'brushes' in electrical equipment."

Page 12: "Metals are elementary substances and do not

decompose, polymerize, carbonize, etc.

Stainless steel has operated as a hot metal container at 1000°F for 1 year.

Page 79: "Mass transfer in liquid metals may be influenced by electrical effects. Transfer of dissolved elements in solid and in liquid metals under the influence of applied potentials, referred to in the literature as electrolytic diffusion, has been observed and studied quantitatively. See also Von Kreman, R., "Electrolysis of Molten Alloys," Sammlung Chemischer und Chemisch--Technischer Vortraege 28, 347-408, 1926. For example, a direct potential of 5 volts with a flow of 20 amperes for periods of less than a day resulted in transfer of microscopic amounts of carbon in gamma iron. No evidence of mass transfer by this means has been observed so far in liquid-metal-heat transfer systems although there is some evidence that application of a potential can be used to inhibit attack. See also: Barnes, A.H., Smith, F.A., Whitham, G., Direct Current Electromagnetic Pumps, ANL-4322, Oct. 25, 1947.

Markert, W., Jr., and Piotler, E. C., B & W Repr. No. ES-401-2. (Project "Baby," NObs-34222), June 9, 1947

Markert, W., Jr., and Piotler, E. C., B & W Repr. No. ES-401-1. (Project "Baby," NObs-34222), April 17, 1947.

Rehn, I, ANL-4029, Sept. 2 1947

"Symposium on Basic Properties of Liquid Metals" held at ANL on April 5, 1949.

Page 80: "Attack on steels by mercury is <u>completely</u> (rate of attack less than 1 mil per year) inhibited by the addition of titanium or zirconium. These inhibitors were found after very extensive and expensive laboratory investigations and though possible explanations have been offered, the mechanism by which they act is not known. Where oxygen is known to accelerate attack by liquid metals, inhibitors are being sought which will tie up the oxygen as as insoluble oxide."

Page 82: "Low-carbon steels have good resistance to attack by flowing Hg below about 400°C (752°F)."

Page 85: "Attack by Hg on ferrous alloys can be reduced to negligible amounts by the addition of an inhibitor to the mercury, the best of which is Ti. In order to insure good heat transfer and to prevent excessive use of the inhibitor, it is also necessary to add a ~~melting~~ wetting agent, the best of which is magnesium." See also: Hacket, H. N., "Mercury for the Generation of Light, Heat and Power," <u>Trans. of the</u> ASME, Oct. 1952, p. 647.

Page 86: Add to .0001-.001 per cent Ti, or .04-.02 per cent Zr.

"Copper in Hg increases its attack on low-C steel."

"In addition to an inhibitor it was found desirable to have a ~~melting~~ wetting agent present in the Hg. It s function is two-fold:

to reduce oxides on steel surfaces so that ~~melting~~ wetting and optimum heat transfer may be realized; and to react with the free oxygen, nitrogen and water vapor in the Hg in order to keep the inhibitor active. Wetting agents must, therefore, have a greater affinity for O_2 and N than both the inhibitor (Ti) and iron."

"Mg has been found effective as a wetting agent with no deleterious effects. Use 20 ppm."

Page 87: "Wolfram, molybdenum, chromium and beryllium can be considered for longtime use as containers of Hg at elevated temperatures."

Silver solder (Ag-Cu-Zn) was drastically attacked on exposure to Hg for 24 hours at 400°C."

"Carbon is negligibly soluble in Hg."

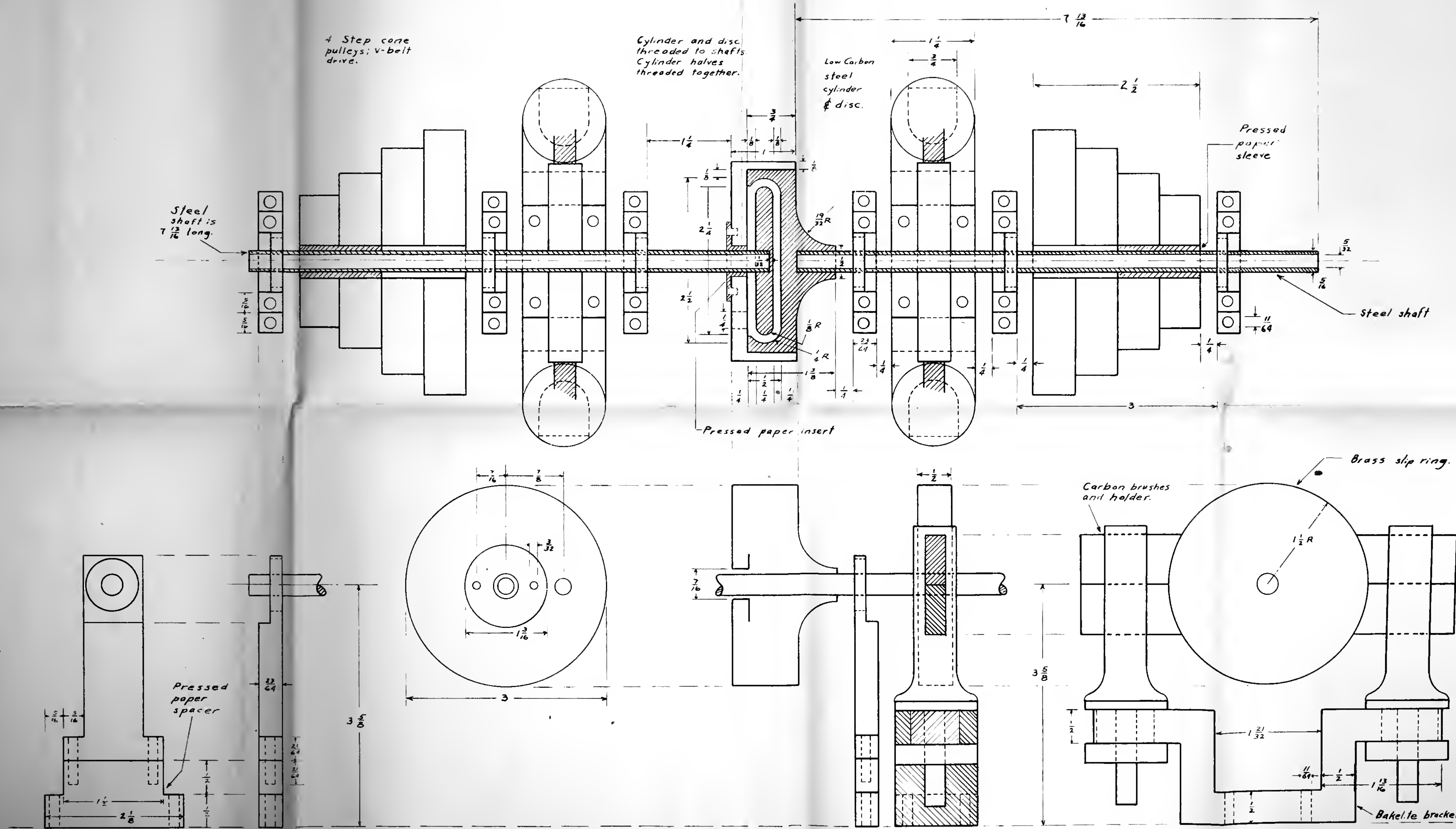


FIG. 1

BRUSH ASSEMBLY DETAIL

HIGH-SPEED MERCURY CONTACT

2 June 1952 R.G. SHULTS

18057
Thesis
S49
Shults
An investigation of mercury as a high-speed electrical contact. 1952.